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日本原子力研究開発機構

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A real-time simulator for both reactor and irradiation facilities of a materials testing reactor, “Simulator of Materials Testing Reactors”, was developed for understanding reactor behavior and operational training in order to utilize it for nuclear human resource development and to promote partnership with developing countries which have a plan to introduce nuclear power plant. The simulator is designed based on the JMTR (Japan Materials Testing Reactor), and it simulates operation, irradiation tests and various kinds of anticipated operational transients and accident conditions caused by the reactor and irradiation facilities. The development of the simulator was sponsored by the Japanese government as one of the specialized projects of advanced research infrastructure in order to promote basic as well as applied researches. This report summarizes the simulation components, hardware specification and operation procedure of the simulator.

Keywords : Simulator, Materials Testing Reactor, Human Resource Development, JMTR, Irradiation Test

＊ ITOCHU Techno-Solutions Corporation

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照射試験炉シミュレータ

日本原子力研究開発機構大洗研究開発センター
照射試験炉センター

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日本原子力研究開発機構では、原子炉挙動の理解及び技能向上を図り、原子力発電所を導入しようとしているアジア諸国をはじめとした国内外の原子力人材育成に貢献するため、照射試験炉シミュレータを開発した。本シミュレータは、文部科学省からの最先端研究開発戦略的強化費補助金のうち、世界最先端研究用原子炉の高度利用による国際的研究開発拠点の整備事業の一環として整備したものであり、照射試験炉の一つである JMTR をベースに設計し、照射試験炉における運転、照射試験、運転時の異常な過渡変化や事故を模擬することにより、これらに対応した原子炉及び照射設備の運転操作訓練を行えるようにした。本報告は、本シミュレータのシミュレーションモデル、ハードウェア仕様及び運転手順についてまとめたものである。

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1. Background

In June 2010, “Birth of the nuclear techno-park with the JMTR [1]” was selected as one of projects of the Leading-edge Research Infrastructure Program by Japanese government. In this project, new irradiation facilities, post irradiation examination facilities, etc. will be installed up to JFY 2013 to build international research and development infrastructure. As a part of this project, a real-time simulator for operating both reactor and irradiation facilities of a materials testing reactor, “Simulator of materials testing reactors”, was developed by Japan Atomic Energy Agency (JAEA) with ITOCHU Techno-Solutions Corporation and GSE Power Systems.

It can simulate the behavior of the materials testing reactor under normal operation condition, anticipated operational transients and accident condition in order to utilize it for a nuclear human resource development and to promote partnership with developing countries which have a plan to introduce nuclear power plant and/or research reactor.

The JMTR (Japan Materials Testing Reactor [2-3]) of the JAEA had been stopped the reactor operation from August 2006, and then the refurbishment works were started in order to ensure safety and increase operating efficiency at the beginning of JFY 2007 [4-6]. In the refurbishment works, especially, the instrumentation and control system were completely upgraded [7]. Therefore, the simulator is designed basically based on the refurbished JMTR [8-10], and treats systems/facilities of the JMTR, e.g. reactor core, primary cooling system, secondary cooling system, emergency cooling system, instrumentation and control systems, safety protection system and electrical system. The simulation model is developed by using the newest and various optimum techniques, codes and tools for real-time simulation with high precision. Furthermore, the simulation model can be modified for future demand by a developed support tool.

The simulator had been designed in JFY 2010, fabricated from JFY 2011, and was successfully completed on May 2012. This report summarizes the simulation of components, hardware, operation procedure of the simulator.

2. Outline of JMTR

The JMTR is a testing reactor with thermal power of 50MW dedicated to irradiation tests of materials and fuels. It achieved first criticality in March 1968. The JMTR is operated with about 30 operation days a cycle.

High neutron flux generated in the JMTR core is utilized for irradiation tests of fuels and materials, as well as for radioisotope productions and human resource development. The JMTR provides various irradiation facilities, such as many types of capsule irradiation facilities, shroud irradiation facility, hydraulic rabbit irradiation facility. Irradiated capsules or specimens are transferred to the hot laboratory, which is connected to the reactor building through a water canal, for post irradiation examinations. Bird’s eye view of the JMTR and hot laboratory is shown in Fig.2.1, and major specifications of the JMTR are listed in Table 2.1. The JMTR consists of a reactor pressure vessel, cooling systems, instrumentation and control systems, electrical systems, and so on.

The reactor operation had been stopped from August, 2006, and then the refurbishment works were started at the beginning of JFY 2007 because of the user's strong request to the JMTR utilization. In the refurbishment works, aged components were investigated, and reactor components such as boiler system, refrigerator, power supply system, air supply/exhaust system, instrumentation and control system, and so on were replaced in order to ensure safety and increase operating efficiency within the range of licensing permission of the JMTR. Especially, the instrumentation and control system was upgraded completely. Moreover, meeting to user's requests, new irradiation facilities, such as test facilities for materials/fuels, production facilities for medical isotopes etc. are being installed. The renewed and upgraded JMTR will be operated for a period of about 20 years.

2.1 Reactor core

(1) Reactor pressure vessel

The reactor pressure vessel, 9.5 m high with 3 m in inner diameter, is made of low carbon stainless steel, and is located in the reactor pool, which is 13 m in depth. Core, current plates, irradiation facilities, etc. are located in the vessel. Cooling water comes from upper part of the vessel, divided into four parts, flows downward and flows to lower plenum. The control rod drive mechanisms are located below the vessel for easy handling of the irradiation facilities and fuels from the upper part of the core. Cutaway view of the reactor is shown in Fig.2.2.

(2) Core

The core of the JMTR is in a cylindrical shape with 1.56 m in diameter and 0.75 m height. It consists of 24 standard fuel elements, 5 control rods with fuel followers, beryllium or aluminum reflectors, H-shaped beryllium frame and an internal shroud. Each cell in the core is about 77 mm square. Cooling water in the primary cooling system is pressurized at about 1.5 MPa to avoid local boiling in the core during normal operation condition. Top view of the core is shown in Fig.2.3, and cross-sectional view of the core is shown in Fig.2.4.

Structures of a standard fuel element and a fuel follower are shown in Fig.2.5. The size of the fuel is about 76 mm square for standard fuel element and about 63 mm square for fuel follower in horizontal cross section, and about 1200 mm and 890 mm in height, respectively. Enrichment of U-235 in the fuel is slightly less than 20 %wt. Side plates of fuel element contain thin cadmium wires as burnable absorbers.

There are five control rods in the JMTR, each consist of the neutron absorber (square–tube of hafnium), fuel follower and shock section. Each rod is driven by the control rod drive mechanism (CRDM). The CRDM consists of inner drive mechanism located inside of control rod canned pipe, and outer following mechanism located outside of it. The inner drive mechanism moves up and down by a reluctance motor that is powered by low frequency alternative current. The outer following mechanism moves vertically, by an excitation electromagnet coil, and keeps its position equal to the height of the inside yoke by the detecting difference between them.

During the operation of the reactor, the electromagnet is activated by the current of the coil, then, the link-latch is fixed in open-shape and holds the control rod. When coil current is cut off at the reactor scram, the electromagnet force is released, and the link-latch is closed. Then, the control rod is detached from the drive mechanism, and it drops quickly by dead weight and cooling water flow force downward in the pressure vessel.

Fuel arrangement of the JMTR for the equilibrium core is shown in Fig. 2.6. Fuels in the JMTR core are consisted of 24 standard fuel elements and 5 fuel followers as mentioned above. Standard fuel elements are used during three cycles. 5 fuel followers are divided into two groups; one is shim rods, SH-1, SH-2 and SH-3, and the other is regulating-safety rods, SR-1 and SR-2. Fuel followers are used during two cycles. Typical reactor start-up and shutdown pattern for full-power at 50MWth is shown in Fig.2.7.

2.2 Cooling system

The cooling systems in the JMTR consist of a primary cooling system, secondary cooling system, pool canal circulation system, UCL (Utility Cooling Loop) and SFC (Spent Fuel Cutting) pool circulation system. Cooling system of the JMTR except for UCL and SFC pool circulating systems is shown in Fig.2.8. An emergency cooling system is a part of the pool canal circulating system in Fig.2.8. The heat generated in the core is removed by the cooling water in the primary cooling system. The cooling water flows downwards in the core, and transfers the heat from the core to the secondary cooling system through heat exchangers. The heat transferred to the secondary cooling system is removed away into the atmosphere in cooling towers.

In the primary cooling system, three main circulating pumps and one emergency pump are operated. An electrical source for two main circulating pumps is commercial power and one main circulating pump and one emergency pump is diesel generator. The primary cooling system has a purification system, and a part of primary coolant at about $50m^3/h$ flows into the purification system which has a deaeration tank and anion and cation towers.

In the secondary cooling system, four circulation pumps, four cooling fans and two auxiliary pumps are installed. The auxiliary pumps are used for removal of decay heat in case of loss of commercial electric power supply. Usually three circulating pumps and two of the three fans are operated. An electrical source for four circulating pumps and three cooling fans is commercial power, and it for one auxiliary pump and one fan is diesel generator.

The emergency cooling system which is in the primary cooling system is used in case of loss of coolant accident in the primary cooling system.

2.3 Instrumentation and control system

Instrumentation and control system in the JMTR consists of nuclear instrumentation system, process instrumentation system, safety protection system and control system. Flow diagram of the system is shown in Fig.2.9.

(1) Nuclear instrumentation system

In the nuclear instrumentation, neutron flux and reactor period in the core which is necessary for start-up, operation and shutdown of the reactor, are measured. The instrumentation consists of a start-up system, logarithmic power system and linear power system, and each system consists of independent three channels. In the logarithmic power system and linear power system, outputs from three channels are compared with each other, and each output deviation of three channels is checked, respectively.

An automatic operation of the reactor is performed using one of three linear power outputs, and the handling of these outputs is based on “two out of three” method. In the operation, the control rod position is adjusted so that reactor power is kept at the required power. When neutron flux reaches at an abnormal level or the nuclear instrumentation has an abnormal condition, the information is delivered to the safety protection system. Fission chambers (FCs) and compensated ionization chambers (CICs) are used as neutron detectors for the nuclear instrumentation.

(2) Process instrumentation system

In the process instrumentation, temperature, flow rate and pressure are measured in each system to perform the safety and appropriate operation. When a measured value reaches at an abnormal level, the information is delivered to the safety protection system.

(3) Safety protection system

There are 5 safety protection actions, “Alarm”, “Stop rod withdrawal”, “Set-back”, “Rod insertion” and “Scram”. They are activated depending on reactor abnormal condition. Flow diagram of the safety protection system is shown in Fig.2.10.

“Alarm” is activated in order to call reactor operator’s attention, and the operator can take proper actions. “Stop rod withdrawal” is activated in case that the reactor power up speed is too fast, and the extraction of the control rod stops temporarily. “Set-back” is activated in case that the reactor pressure or pressure difference between inlet and outlet pressure exceeds a predetermined level in the automatic reactor operation. “Rod insertion” is activated by signals from the nuclear instrumentation, process instrumentation and irradiation facilities in the automatic reactor operation. By this action, all control rods are inserted separately according to the predetermined sequence. The JMTR has two types of “Scram”; one is “Fast Scram” which is activated by abnormal condition in the nuclear instrumentation, and the other is “Slow Scram” which is activated by abnormal condition in other instruments. When the control mechanism has trouble in the “Scram”, the Back-up scram system is activated. Then poison liquid solution is injected in the primary cooling system and the reactor becomes a subcritical condition.

(4) Control system

The JMTR has 5 control rods and one emergency reactor shutdown system. 5 control rods consist of 3 shim rods and 2 regulating-safety rods. One of the regulating-safety rods is used as a fine adjustment rod, and its control range is 550mm to 650mm during the automatic operation. Control range for all shim rods is 0mm to 800mm. Driving speed of shim rods is about 200mm/min at high speed, and about 40mm/min at low speed. Driving speed of regulating-safety rod is about 200mm/min in manual reactor operation, and 0 to 2000mm/min in automatic reactor operation.

2.4 Electrical system

The JMTR electrical system has 2 main power line which are the commercial power line and diesel engine generator line. The diesel engine power line has, additionally, constant-voltage constant frequency power line, and DC battery power line. Important equipment for the reactor operation is connected to the diesel engine generator so that decay heat is removed steadily in case of the loss of commercial power supply.

2.5 Irradiation facility

Many types of irradiation facilities have been developed in the JMTR. Six typical facilities are described as follows.

(1) Capsule irradiation facility with temperature control by heater and gas pressure

Specimens are inserted in a capsule, and the capsule is inserted into an irradiation hole in the core. Each specimen is heated by nuclear heating due to neutron and gamma ray, and its temperature varies with reactor power, position of control rods and cooling condition during reactor operation. Temperature of a specimen in the facility can be controlled by heater and gas pressure.

(2) Capsule irradiation facility with neutron fluence control

Inner capsules with specimens are installed into a capsule, and neutron fluence can be controlled by movement of the inner capsule in the capsule. This movement is done by helium gas pressure. Temperature is also controlled by heater.

(3) Irradiation Environment Control Device (BWR)

The facility is used to carry out the irradiation test under controlled conditions of temperature, pressure, radiation and water quality with BWR environment. The facility is composed of saturated temperature capsule inserted into the core and the water control unit that supplies high-temperature and high-pressure water.

(4) Shroud irradiation facility

The facility consists of the Oarai Shroud Facility-1 (OSF-1), the Boiling Water Capsule (BOCA) pressure control system and ^{3}He gas pressure control system. In-pile tube of the OSF-1 is penetrated into the core through the top lid of the reactor pressure vessel, and forms independent pressure boundary by independent cooling system. The BOCA is a high pressure capsule made of stainless steel in which instrumented segment fuel is loaded, and is cooled by the pressurized water. The BOCA is inserted into the in-pile tube of the OSF-1, and power ramping test is performed by controlling ^{3}He gas (acting as neutron absorber) pressure in the ^{3}He gas screen in the in-pile tube by a ^{3}He gas pressure control system.

(5) Hydraulic rabbit irradiation facility

Hydraulic rabbit irradiation facility is a water loop system to transfer the small sized (150mm length) capsule, so called rabbit, into and out from the core by the water flow in the loop during reactor operation. Maximum number of rabbits for loading is three, and these rabbits are loaded into core one by one.

(6) OWL-2 irradiation facility

The OWL-2 irradiation facility, which executes irradiation test for fuel and material of light water reactor, is a large in pile loop with high temperature and high pressure water. The facility is composed of primary cooling system, secondary cooling system, safety and control system, etc.

3. Simulation of components

3.1 Scope of simulation

The scope of simulation by the simulator is a reactor core, primary cooling system, purification system, secondary cooling system, emergency cooling system, electrical system, safety protection system, nuclear instrumentation system and irradiation facilities in a materials testing reactor, and each simulation model is designed based on the refurbished JMTR. The simulator does not include the part of pool canal circulating system, the UCL system, the SFC pool circulating system and the exhaust system.

The simulator covers normal operations, anticipated operational transients and accident conditions such as LOCA, and also covers start-up, full power operation, shutdown operation and irradiation tests in the reactor. In order to build and execute the simulator, various components and tools are used such as REMARK, RELAP5-HD, TRUMP, JADE, etc in the SimExec [11] simulator environment. The SimExec is the master simulation database, compiler and configuration management tool used to interface the various integrated or related systems and sub-system into a single real time executables.

Codes and tools for the simulation are summarized in Table 3.1. The JADE [12] is a suite of simulator developing tools with an easy to use graphical front end, written in Java.

3.2 Reactor core

3.2.1 Modeling by REMARK

The reactor core is modeled with Real-time Multigroup Advanced Reactor Kinetics code, REMARK [13] developed by GSE Systems, inc., in which a three-dimensional, time dependent, and diffusion theory model are applied. The REMARK model is modified to use four energy group for more accuracy. The REMARK is capable of simulating the core neutron physics during normal operation, anticipated operational transients and accident conditions. The REMARK can also treat following functions:

(1) Delayed neutron contribution in each mesh
(2) Burn-up calculation of fissile nuclide such as ^{235}U
(3) Poison calculation such as ^{135}Xe and ^{149}Sm
(4) Decay heat calculation

The REMARK model of the reactor core consists of 236 assemblies with 984 nodes. 116 radial nodes simulate 24 fuel elements and 5 control rods. Axially, the model consists of 20 nodes. The REMARK model, the radial nodalization and the axial nodalization are shown in Fig.3.1, Fig.3.2 and Fig.3.3, respectively. The REMARK model is executed with a frequency of about 40 Hz.

3.2.2 Boundaries with REMARK

(1) Control rod drive mechanism

The REMARK model treats the control rod drive mechanism (CRDM). The CRDM specifies the rod positions depending on demand signal, CRDM power supply, malfunctions etc. The nodalization of a moving neutron absorber and fuel follower of the control rod in the core is shown in Fig.3.3. During the movement of the control rod, the material composition in the computational node varies dynamically with changing the fraction of all material in the node to calculate the cross section data at any control rod position.

(2) Nuclear instrumentation

The REMARK model is connected with nuclear instrumentation (NI) model. The NI models read neutron flux data calculated by the REMARK in the reactor core model, and the NI information is used in the control logic to regulate the CRDM to keep the required reactor power. Fission chambers (FC) and compensated ionization chambers (CIC) are set as neutron detectors as already mentioned in section 2.3.

(3) Reactor cooling system

The REMARK model is connected with the reactor cooling system with RELAP5-HD [14] thermal hydraulic model by providing power to moderator. The RELAP5-HD, real time version of well proven best estimated code RELAP5-3D developed by Idaho National Laboratory, provides thermal hydraulic feedback to the REMARK. The thermal hydraulic and neutronics parameters exchanged between the REMARK and the RELAP5-HD are listed in Table 3.2. The RELAP5-HD models the core as six radial channels and three axial nodes. The RELAP5-HD model provides thermal-hydraulic parameters to the respective radial and axial nodes of the REMARK model. Since there are more node numbers in the REMARK model than that in the RELAP5-HD model in the reactor core, the generated power in all REMARK nodes that are included under a specific RELAP5-HD reactor core channel is summed up and is provided to the RELAP5-HD heat structure nodes. Radial nodalization of the RELAP5-HD model is shown in Fig.3.4, and axial nodalization of the RELAP5-HD model and the REMARK model is shown in Fig.3.3.

(4) Irradiation facilities

Following six irradiation facilities (IFs) are incorporated with the simulator.

1) Capsule irradiation facility with temperature control by heater and pressure
2) Capsule irradiation facility with neutron fluence control
3) Irradiation environment control device (BWR)
4) Shroud irradiation facility
5) Hydraulic rabbit irradiation facility
6) OWL-2 irradiation facility

Preconditions for connection between the core and IFs in the simulator are as follows. Nuclear heating and neutron flux in facilities are given by the core, and reactivity to the core is given by fluctuation of materials in the IFs. Core coolant condition does not change due to heating in facilities as it is deemed negligible. When a specimen in a capsule moves axially, the material composition will change dynamically in computational cell. However, the composition change is set to occur instantly except for the shroud irradiation facility in the simulator. In the shroud irradiation facility, as the BOCA is inserted to the OSF-1 or withdrawn from the OSF-1 by the speed of 1m/min, the cross section changes dynamically based on the axial fractions of all materials in and out of the node. In order to calculate the heat generation in the three dimensional geometric structure of each irradiation facility, TRUMP [15], the partial differential equation solving code, has been converted to run in real-time.

3.2.3 Preparation of cross section

The reactor core consists of following elements, and radial model of each element is shown in Fig.3.5, Fig.3.6 and Fig.3.7.

(1) Standard fuel element
(2) Control rod with fuel follower
(3) Aluminum or beryllium reflector element
(4) Reactivity adjustment rod
(5) Irradiation facility

Cross sections for these elements are generated in four energy groups using the lattice code, SRAC2006 [16], and the neutron cross section library, JENDL-3.3 [17], over about 77 mm squared cells. These cross sections depend on core conditions such as void fraction of coolant, fuel temperature and coolant temperature. Therefore, each cross section for each core condition is prepared in advance at the same way as the safety evaluation at the JMTR [18-19], and prepared cross sections are listed in Table 3.3.

Cross sections used in the REMARK calculation are interpolated ones. Furthermore, cross sections for the standard fuel elements and fuel followers are prepared in advance at fuel burn-ups 0, 1.0, 2.0, 3.0, 4.0, 5.0, 7.0, 8.5, 10.0, 15.0, 20.0, 25.0, 30.0, 50.0, 60.0 and 95.0%.

As for irradiation facilities in a materials testing reactor, various kinds of materials are irradiated as specimens in the designed capsule, respectively. Therefore, “Irradiation Facility Design Support system (IFDS system)” was developed to calculate averaged cross sections for irradiation facilities one by one in the simulator.

Materials and geometries of capsule components including specimens can be changed by using the IFDS system. After the design, the system generates cell averaged cross sections for the facility using SRAC2006 and the JENDL-3.3. The GUI (Graphical User Interface) of the system is shown in Fig. 3.8.

3.2.4 Core arrangement

In a materials testing reactor like the JMTR, it is possible to carry out irradiation tests with various required irradiation conditions such as neutron flux, temperature, environment, material or dimension of specimen by its core structure and various types of irradiation facilities with high irradiation technologies. The core arrangement changes in each cycle depending on design, type or position of loaded irradiation facility in the reactor core. Neutronic characteristic of the reactor core also changes in each cycle. Therefore, the simulator can change core arrangement easily by the following procedure in order to simulate such a condition.

Operator can exchange the cell to another cell in the core except for standard fuel element cells and control rod cells by using “Cell Distribution Support system (CDS system)”. For example, the operator can exchange an aluminum reflector for a beryllium reflector or a reactivity adjustment rod for an irradiation facility on the GUI of the CDS system, and prepared cross sections in advance or generated ones by the IFDS system are set for the core calculation automatically. The GUI of core arrangement and core element selection in the CDS system are shown in Fig3.9 and Fig.3.10, respectively.

3.3 Cooling system

3.3.1 Modeling by RELAP5-HD

Two thermal hydraulic codes, RELAP5-HD and JTopmeret [20], are used in the simulator. The RELAP5-HD is used for the reactor pressure vessel in order to model the void coefficient feedback loop accurately in the core, and the JTopmeret is used outside the vessel.

The Reactor is composed of the reactor pressure vessel, the core, the CRDM, etc. The simulation model of the reactor pressure vessel is designed by using standard components for volumes and junctions in RELAP5-HD. The model is designed so that cold water of the primary coolant, coming from JTopmeret model, enters the reactor pressure vessel model. In the cavities below the reactor core, the coolant flows down and leaves the reactor pressure vessel through connection to the model of the primary cooling system (JTopmeret model).

The RELAP5-HD model is designed by employing non-equilibrium, non-homogenous, two-phase flow option, and the nodalization of the model is divided into two parts, the thermo-hydraulic nodes and the heat structure models within the RELAP5-HD. The thermo-hydraulic model consists of 43 one-dimensional nodes. The thermo-hydraulic model of the reactor by RELAP5-HD is shown in Fig.3.11.

In order to calculate the void coefficient more accurately, the nodalization of the thermo-hydraulic cooling channels (THCC) is defined, thus, five THCCs and one bypass channel (BPC) are used. These channels are all subdivided into three axial volumes.

Heat structure models are used to represent solid structures such as fuel plates, the reactor pressure vessel wall and reflectors in order to calculate the heat transferred across solid boundary of hydrodynamic volumes. The nodalization and heat structures are shown in Fig.3.12. To these channels, a number of heat structures with different functions are attached.

The heat generation inside fuel plates and conducting heat from the center part of fuel plates to the coolant between plates are represented as the most important heat structure model. The center part of the fuel plate has a symmetry condition while a hydraulic boundary is connected to the THCC volumes on the surface of the plate. There are thirty elements of heat structures (six per one thermo-hydraulic cooling channel) where the nuclear heat is added. Heat structure model of the fuel plate is shown in Fig.3.13.

Moreover, there are heat structures for simulation of heat generation inside reflectors' material and heat transfer to the bypass channel (HSBP-02). The reactor pressure vessel is submerged in a reactor pool. In order to simulate a heat exchange between the coolant inside the reactor pressure vessel and the water in the reactor pool, heat structure models for the heat flow through the wall of the reactor pressure vessel are introduced by using the JTopmeret.

3.3.2 Modeling by JTopmeret

In order to simulate cooling loops, purification system and cooling towers, JTopmeret in the JADE tool, a six equation, two phase thermo-hydraulic modeling tool developed by GSE systems, Inc. is applied. Flow rates, pressures, temperatures and so on are calculated in the cooling loop model with depending on the state of plant equipments such as pumps, valves, external parameters. As for the primary cooling system, these parameters are provided to the RELAP5-HD model via an inlet pressure boundary, and the reactor outlet flow is received via a flow boundary.

The simulated cooling systems are primary, purification, secondary, pool canal cooling system, and drain system.

3.4 Instrumentation and control system

The instrumentation and control system represented in section 2.3 is incorporated with the simulator. The model of the safety protection system is modified for the simulator as follows.

“Fast Scram” and “Slow Scram” are brought into “Scram”, and “Set-back” is brought into “Rod insertion”. Incidents such as “Earthquake” and “RUN safe switch” in Fig.2.10 are performed using malfunctions described in section 3.6. The Back-up scram system is also incorporated with the simulator. The instrumentation and control system is developed by Jlogic [21] in the JADE tool.

3.5 Electrical system

The electrical system represented in section 2.4 is developed by JElectric [22] in the JADE tool. The model of the electrical system modified for the simulator is shown in Fig.3.14.

3.6 Malfunctions

Malfunctions are out-of-model behavior of the simulator. That means simulator dynamics are not part of the standard dynamic behavior of the physical models. Typical selected malfunctions based on the analysis results in the JMTR [23] for the simulator are listed in Table.3.4. Moreover, standard equipments such as pumps, valves, check valves, transmitters, etc. in cooling systems are modeled by the JTopmeret. Electro-mechanical properties for these components are simulated individually, and are generated automatically from a database. Each type of components has a number of default built in malfunctions, so that the instructor can initiate an arbitrary equipment malfunction such as a tube rupture or degradation of equipment. Therefore, a lot of different accident scenarios are realized and analyzed with the simulator.

3.7 Other components

All reactor control relays and DCS (Distributed Control System) control logics are simulated in

JControl [24] in the JADE tool, and the same regulation and safety logics to the simulator are provided as they act as an actual reactor. The hardware panels in the actual reactor are fully or partially emulated with soft panel pictures as operation screen by JDesigner in the JADE tool. The DCS MMI (Man-Machine Interface) pictures are also fully emulated with the JDesigner.

Operation screens of the reactor control system and cooling systems are shown in Fig.3.15, Fig.3.16, Fig.3.17 and Fig.3.18, Fig.3.19 and Fig.3.20, respectively. As for irradiation facilities, operation screens of the shroud irradiation facility and the hydraulic rabbit irradiation facility in the simulator are shown in Fig.3.21 and Fig.3.22 as examples.

In these screens, there are equipments with white spot which means that the valve can be opened, closed or adjusted to control the flow rate in case of the valve. Outside air temperature and humidity are shown in Fig.3.18, and these values can be changed by the instructor. Changes of these values affect secondary coolant temperature and reactivity in the core as a result. All of the mentioned systems run at an execution frequency at about 40 Hz.

The simulation model is constructed based on the refurbished JMTR as mentioned above. On the other hand, in order to respond to future modification such as division/addition of malfunction, irradiation facility, equipment in cooling system, etc. with comparative ease, support tools for simulator development is also provided using the JADE tool.

4. Hardware

4.1 Configuration of simulator

The simulator consists of a reactor control panel, process control panel, irradiation facility control panel, instructor control panel, process server, etc. The reactor control panel has two PCs and other panels have one PC, respectively. There are two large size monitors for the reactor control panel, and a large size monitor for each control panel. The large monitor for instructor is touch panel type for efficient lecture. A schematic drawing of the hardware configuration is shown in Fig.4.1, and overall photograph of the simulator room is shown in Fig.4.2. A photograph of each control panel and the process server are shown in Fig.4.3.

4.2 Specification of component

Specifications of simulator components are listed in Table 4.1, and general description of main components are as follows.

(1) Reactor control panel

The reactor control panel is used for reactor operation. The reactor control panel is made by hardware for practical training, and other control panels are realized in PCs. The reactor control panel is designed based on the refurbished JMTR. There are several indicators in the actual machine.

However, these indicators are arranged on a versatile monitor set in the panel because of easy modification in future. A photograph of the panel is shown in Fig.4.3, and outer shapes of the panel are shown in Fig.4.4 and Fig.4.5.

(2) Process control panel

The process control panel is used for process operation such as cooling systems. The DCS MMI pictures of the refurbished JMTR are emulated in the panel, and cooling systems can be operated with the mouse and the keyboard.

(3) Irradiation facility control panel

The irradiation facility control panel is used for operation of each irradiation facility introduced in the simulator. The DCS MMI is designed and arranged based on an each irradiation facility in order to control the each facility fully by only the panel.

(4) Instructor control panel

The instructor control panel is used to run and control the simulator by the instructor. Main functions are as follows.

(1) Loading and storing of initial conditions (snapshots)
(2) Running and freezing of execution
(3) Changing time scales
(4) Setting and activating malfunctions and remote functions
(5) Displaying various figures, graphs and data output
(6) Keeping record of the operator’s actions for later examination
(7) Backtracking and replaying the simulator from an earlier time step

(5) Process server

Calculations such as neutronics, thermo-hydraulics, etc. for simulation are carried out by the process server.

5. Operation procedure of simulator

5.1 Preparation for operation

In order to operate the simulator by each required condition of the irradiation test like a materials testing reactor, following items are necessary to be prepared in advance.

(1) Selection of irradiation facility represented in section 3.2.2.
(2) Design of irradiation facility by using IFDS represented in section 3.2.3.

(3) Core arrangement by using CDS system represented in section 3.2.4.

5.2 Operation procedure

Following ordinary and transitional operation can be simulated by the simulator like a materials testing reactor using the reactor control panel, the process control panel and the irradiation facility control panel in accordance with the prepared operating manual.

(1) Start-up, ordinary and shut-down operation for cooling system operating valves, pumps, etc.
(2) Start-up, criticality search, power-up, full power operation and shutdown of the reactor
(3) Activation of safety protection system in case of deviation conditions
(4) Operation of irradiation facilities
(5) Activation of malfunctions

Operating parameters such as the coolant flow, the coolant temperature, the fuel temperature, coolant pressure, the reactor power and the reactor period are calculated and monitored on the reactor control panel, process control panel and large size monitors for efficient trainings. These can be seen in Fig.4.2 and Fig.4.3.

Power distribution in the fuel, k_{eff} trend in the core, etc. which cannot be seen in an actual reactor are monitored in real time in the simulator. A typical display of reactor parameters, k_{eff}, control rod positions and thermal power is shown in Fig.5.1. The figure shows the fluctuation of the k_{eff} and the thermal power when one of the control rods has been withdrawn and stopped. Coolant and fuel temperature in the reactor pressure vessel and neutron flux in the core can be also monitored in real time. Outputs of coolant and fuel temperatures in the reactor pressure vessel and neutron flux distribution at the core operated at 50MWth are shown in Fig.5.2 and Fig.5.3, respectively.

6. Summary

A real-time simulator for operating both reactor and irradiation facilities of a materials testing reactor, “Simulator of materials testing reactors”, was developed and completed on May 2012 by the JAEA based on the refurbished JMTR. It can simulate the behavior of the materials testing reactor under normal operation condition, anticipated operational transients and accident conditions with high precision, and the simulation model can be modified with comparative ease to respond future training requests.

Training of simulated operation using the simulator has been started at the training course for foreign young researchers and engineers in August 2012, and the simulator will be continue to contribute the nuclear human resource development and also training for operators of both reactor and irradiation facilities for safe and stable operation of a materials testing reactor.

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Table 2.1 Major specification of JMTR

Reactor type		Light water moderated and cooled tank type
Thermal power		50MW
Neutron flux	Fast (Max.)	4×10^{18} n／m^2･s
	Thermal (Max.)	4×10^{18} n／m^2･s
Fuel element	^{235}U enrichment	20wt%
	Fuel meat	U_3Si_2-Al
	Cladding material	Aluminum
Reflector		Beryllium
Power density		425 MW/m^3
Primary coolant	Core inlet temperature(Max.)	49℃
	Core outlet temperature	56℃
	Flow rate	6,000m^3/h
	Operating pressure	1.5MPa
Irradiation facility	Capsule (Irraditation positions)	200
	Shroud irradiation facility	1
	Hydraulic rabbit irradiation facility	1

Table 3.1 List of simulator codes and tools

Name	Description
REMARK(*1)	Three-dimensional Real-time Multi-group Advanced Reactor Kinetics code
RELAP5-HD(*2)	Thermal hydraulic code
TRUMP	Heat transfer calculation code
JADE(*1)	Simulator development tools SimExec: Master simulation database, compiler and configuration management tool JTopmeret: Thermal hydraulic code JElectric: Electrical network development tool JContrl: System logic development tool JStation: Instructor station development tool JDesigner: Soft panels and diagrams development tool
SRAC2006	Comprehensive neutronics calculation code
JENDL-3.3	Evaluated nuclear data library

(*1) Codes or tools developed by GSE Systems, Inc.

(*2) Real time version of RELAP5-3D developed by Idaho National Laboratory

Table 3.2 Parameter exchange between RELAP5-HD and REMARK[9]

Parameter	Unit	From process model	To process model
Power	W	REMARK	RELAP5-HD
Coolant density	g/cm^3	RELAP5-HD	REMARK
Vapor density	g/cm^3	RELAP5-HD	REMARK
Coolant temperature	K	RELAP5-HD	REMARK
Vapor temperature	K	RELAP5-HD	REMARK
Vapor void fraction	-	RELAP5-HD	REMARK
Fuel temperature	K	RELAP5-HD	REMARK

Table 3.3 List of prepared cross sections

Element	Void ratio (%)	Fuel temp. (K)	Coolant temp. (K)
Standard fuel element	0, 3, 5, 10, 20	325	325
	0	325	300, 350, 400, 500
	0	300, 350, 400, 500, 900	325
	0	293	293
Fuel follower	0, 3, 5, 10, 20	325	325
	0	325	300, 350, 400, 500
	0	300, 350, 400, 500, 900	325
	0	293	293
Control rod	0, 3, 5, 10, 20	325	325
Al reflector in fuel region	0	293	293
	0	325	325
	0	293	293
Al reflector in reflector region	0	325	325
	0	293	293
Be reflector	0	325	325
	0	293	293
Gamma-ray shield plate	0	325	325
	0	293	293
Joint (for fuel follower)	0	325	325
	0	293	293
Shock section (for fuel follower)	0	325	325
	0	293	293
Mix [H_2O+Al] (for fuel)	0, 3, 5, 10, 20	325	325
	0	293	293

Table 3.4 Typical malfunctions

No	System name	Item	Outline
1	Reactor core / Control rods	Unusual extraction of control rod at start-up condition	Positive reactivity addition of about 0.15% $\Delta k/k$ at 500kW
2	Reactor core / Control rods	Unusual extraction of control rod at normal condition	Positive reactivity addition of about 0.5% $\Delta k/k/s$
3	Reactor core / Irradiation facility	Reactivity addition by irradiation specimen	Step positive reactivity addition of about 0.2% $\Delta k/k/s$ due to pull of specimen
4	Electric system	Loss of commercial electric power	Decrease of primary coolant flow due to stop of two primary cooling pumps
5	Electric system	Loss of all electric power	Stop of primary and secondary coolant flow
6	Reactor core / Irradiation facility	Abnormal reactivity addition due to damage of a irradiation facility	Positive reactivity addition of about 0.5% $\Delta k/k/s$ due to fall of a irradiation specimen
7	Primary cooling system	Outflow of primary coolant	Outflow of primary coolant due to damage of a primary coolant pipe
8	Control and logic	Earthquake	Trips earthquake detection relay

Table 4.1 Specification of simulator component

Item	Spec	
PC for Process server : HP ProLiant ML370 G6	CPU Memory Harddisk Optical media OS Screen	2 x E5560 2.8GHz 12 Gb 2 x 450Gb 10000rpm SAS (Raid 1) DVD RW Microsoft Windows Server 2008 Ultimate R2 1 x HP 19” Wide TFT Black HDMI,DVI-D,VGA
PC for Reactor control panel : 2 x HP Compaq Elite MT/CT	CPU Memory Hard disk OS Screen	Core2 Duo E8600 3.33GHz 4Gb DDR3 SDRAM 2 x 160Gb (Raid 1) Microsoft Windows 7 Ultimate 2 x HP 27” Wide TFT Black HDMI,DVI-D,VGA
PC for Process, Irradiation facility and Instructor control panel : 3 x HP Compaq Elite MT/CT	CPU Memory Hard disk OS Screen	Core2 Duo E8600 3.33GHz 4Gb DDR3 SDRAM 2 x 160Gb (Raid 1) Microsoft Windows 7 Ultimate 2 x HP 23” Wide TFT Black HDMI,DVI-D,VGA
Large LCD Screen	4 x Sharp PN-S655 65” Wide TFT Black HDMI,DVI-D, VGA	
UPS	Smart-UPS 1000 Control Soft : Power Chute Business Edition Deluxe for Windows	
Color printer	Fuji Xerox DocuPrint C3350 NL300034	
Switching hub	IO Data ETG2-SH16N Support 1000BASE-T	
Signal selector for large size monitors	Gefen HDMI-Switch	

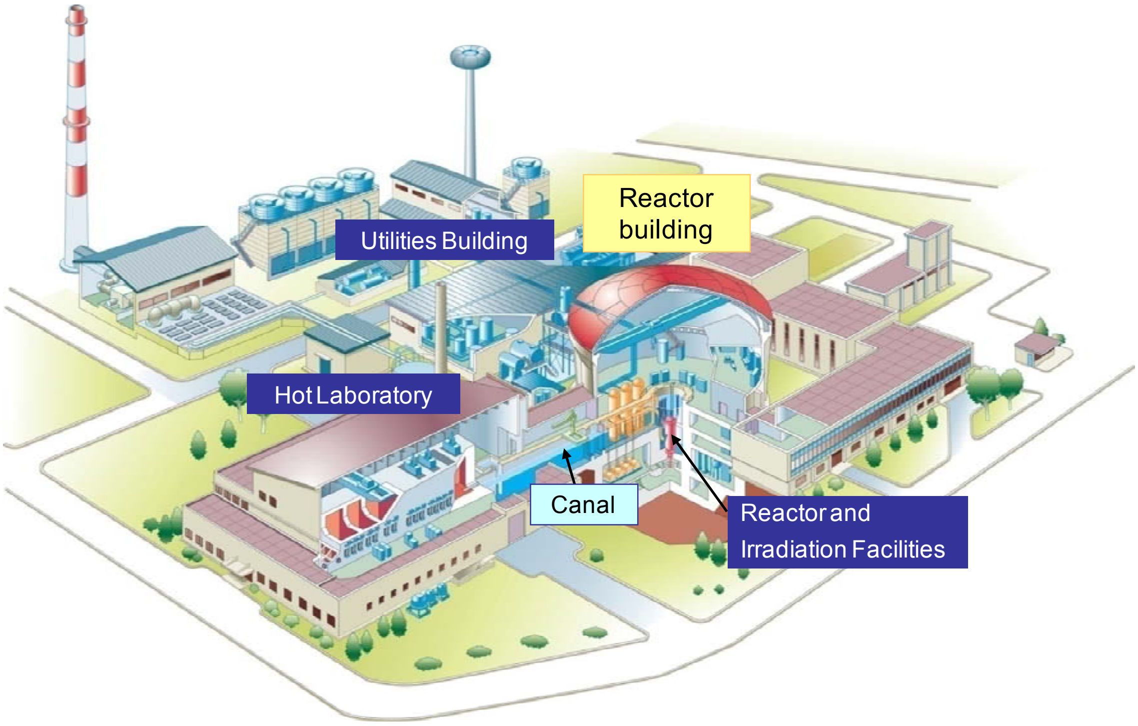


Fig.2.1 Bird's eye view of JMTR and hot laboratory

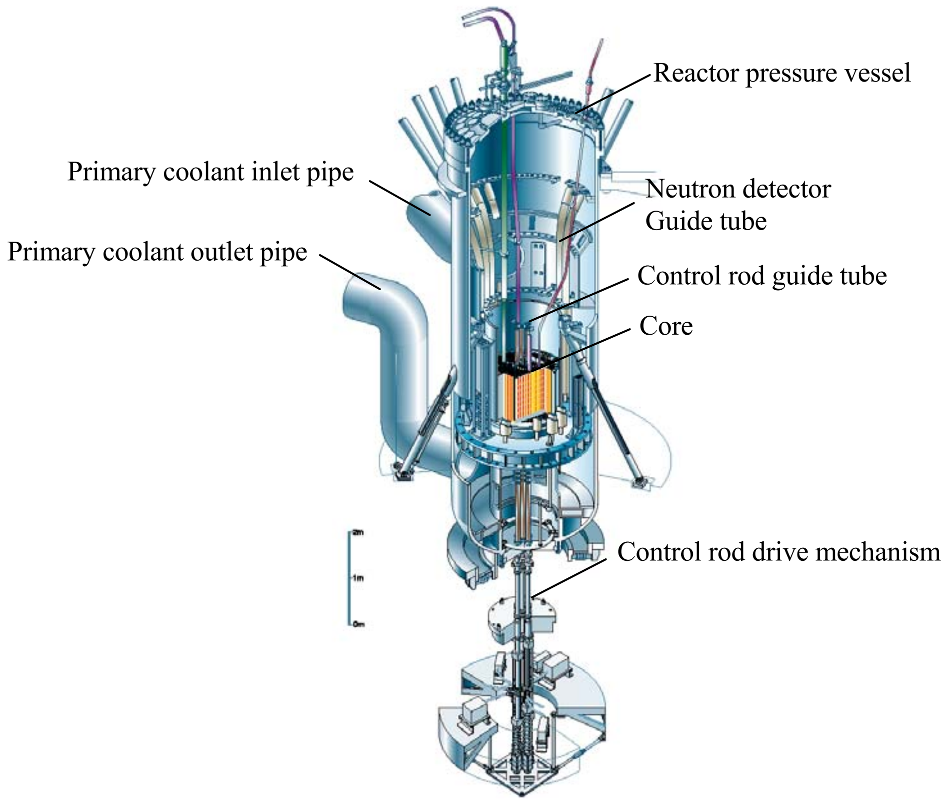


Fig. 2.2 Cutaway view of reactor in the JMTR

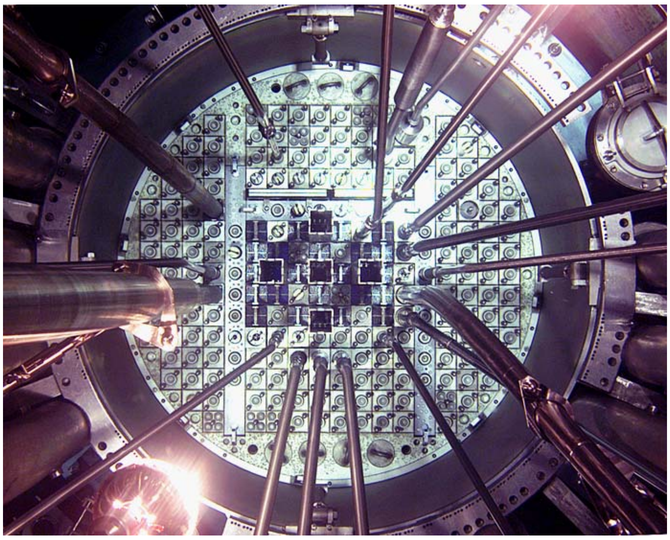


Fig.2.3 Top view of the JMTR core

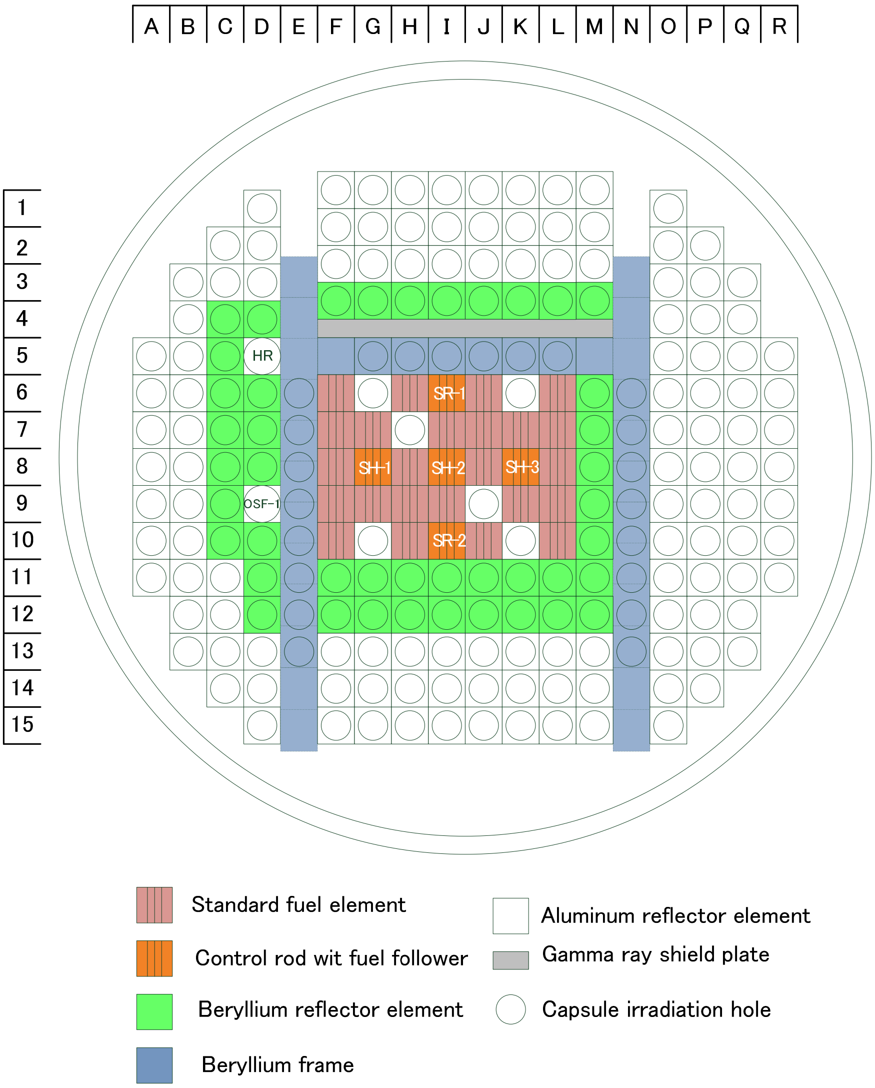
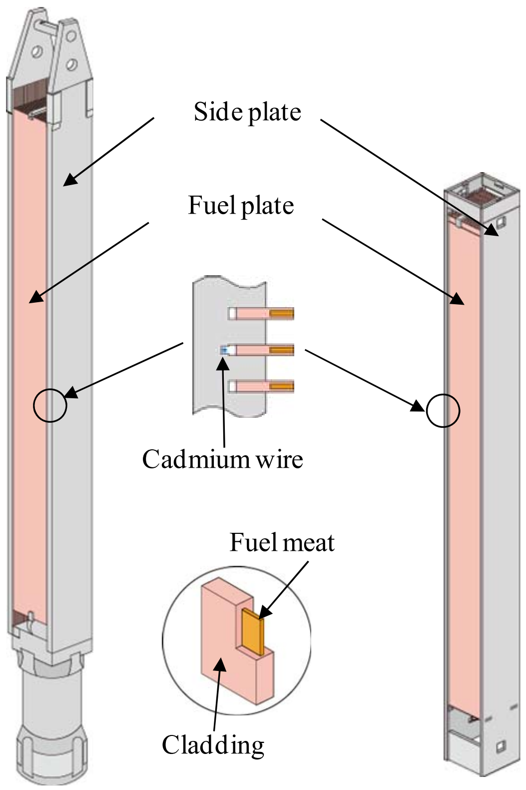


Fig.2.4 Cross-sectional view of the JMTR core



(a) Standard fuel element (b) Fuel follower

Fig.2.5 Structures of standard fuel element and fuel follower of the JMTR

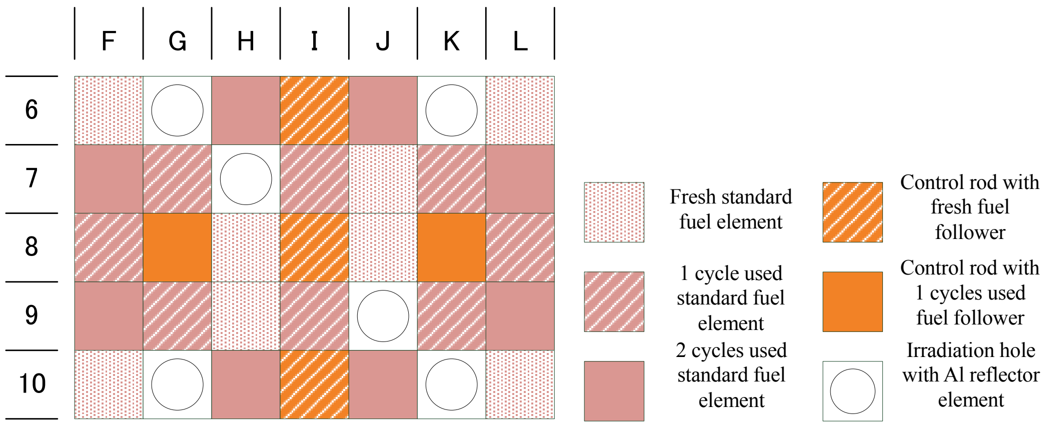


Fig.2.6 Fuel arrangement in equilibrium core in the JMTR

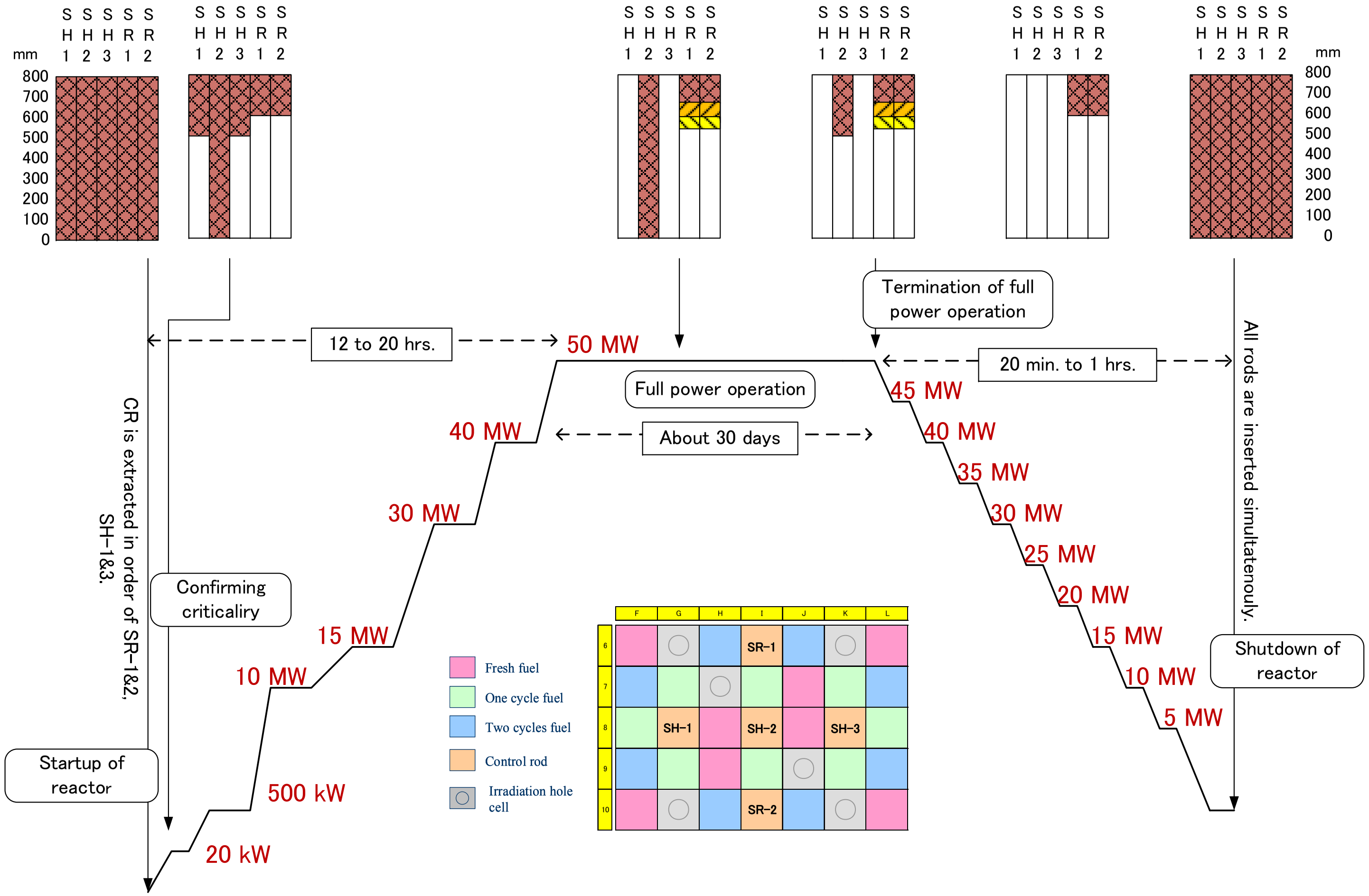


Fig.2.7 Reactor operating pattern in a cycle in the JMTR

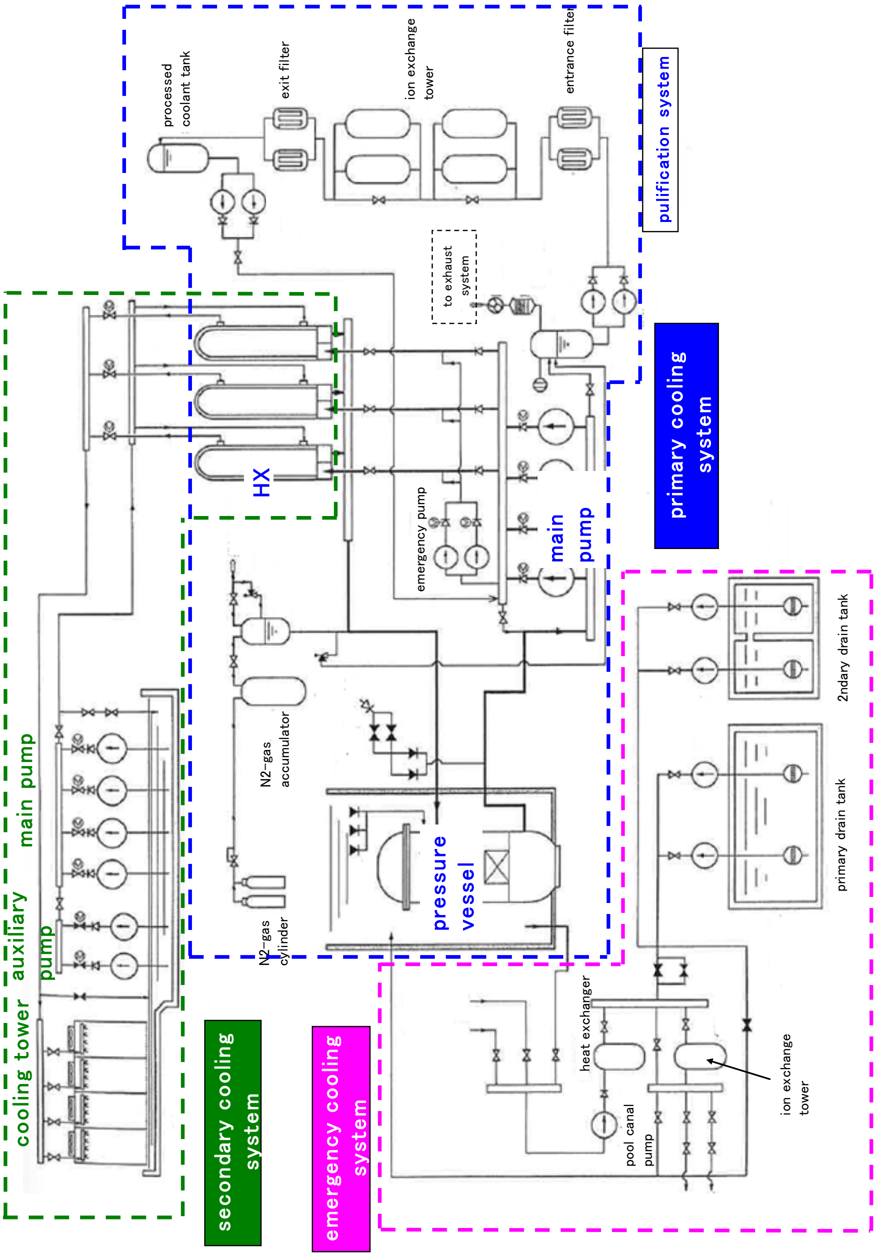


Fig.2.8 Flow diagram of cooling system of the JMTR

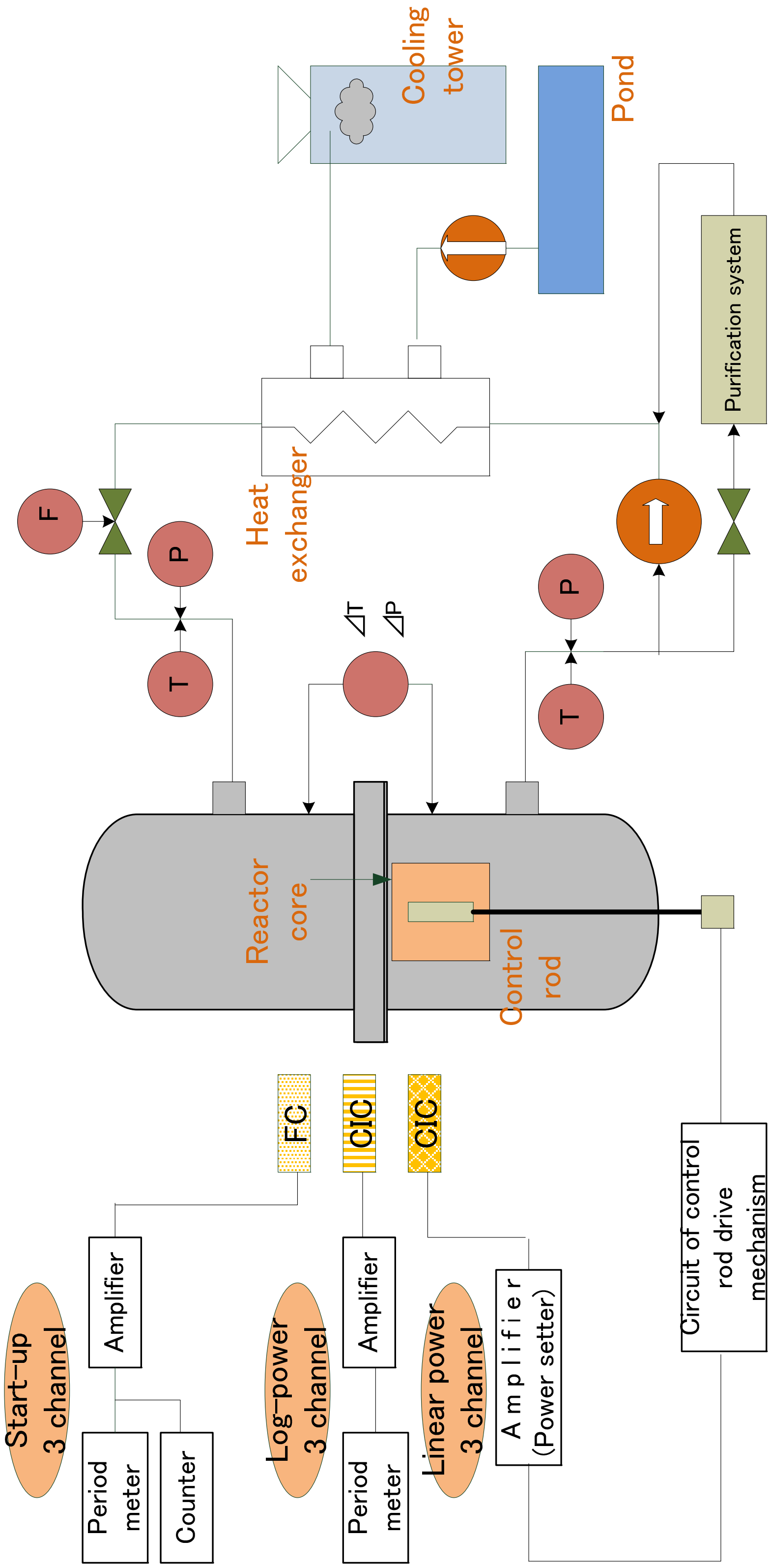


Fig.2.9 Flow diagram of Instrumentation and control system in the JMTR[8]

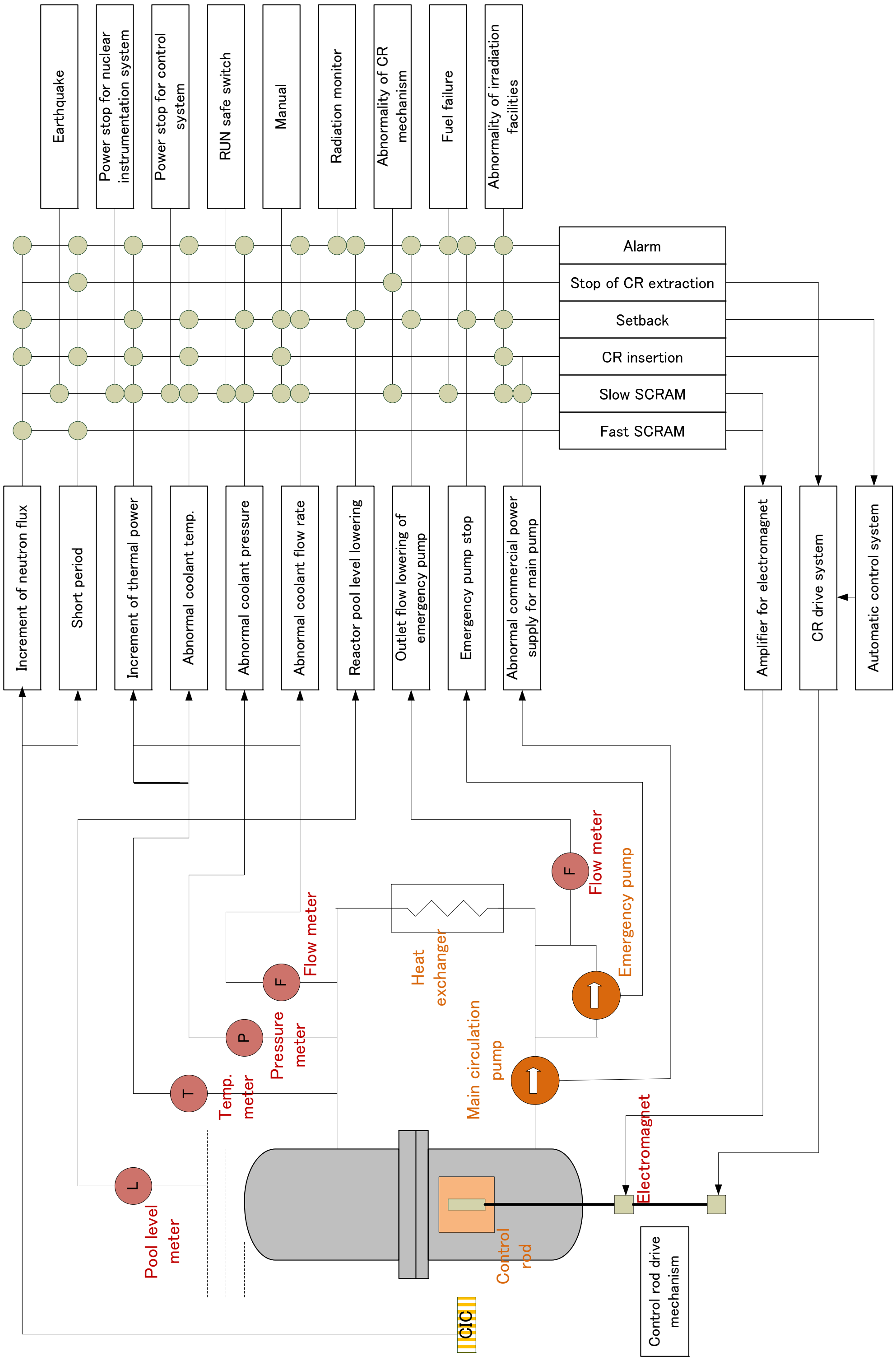


Fig.2.10 Flow diagram of Safety protection system in the JMTR

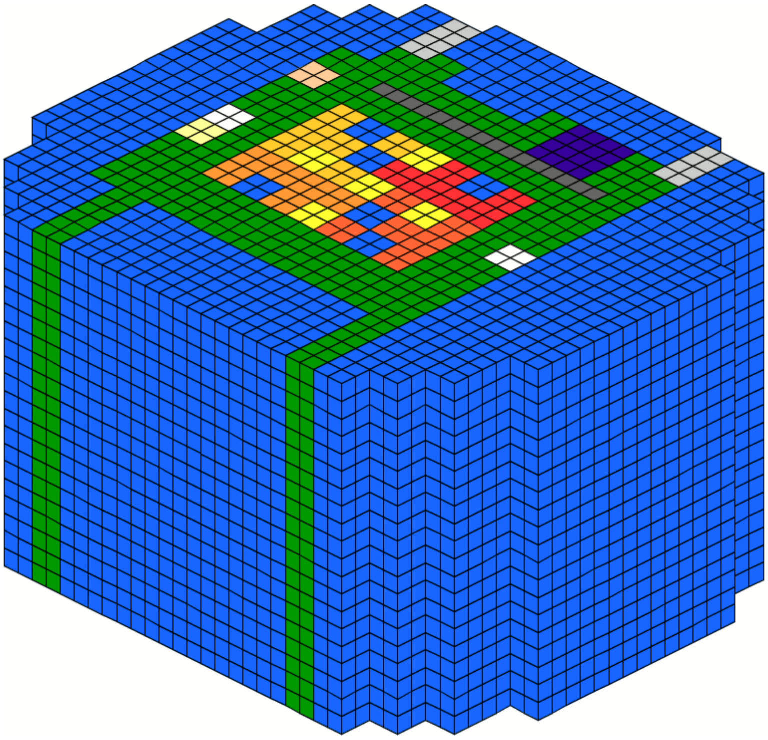
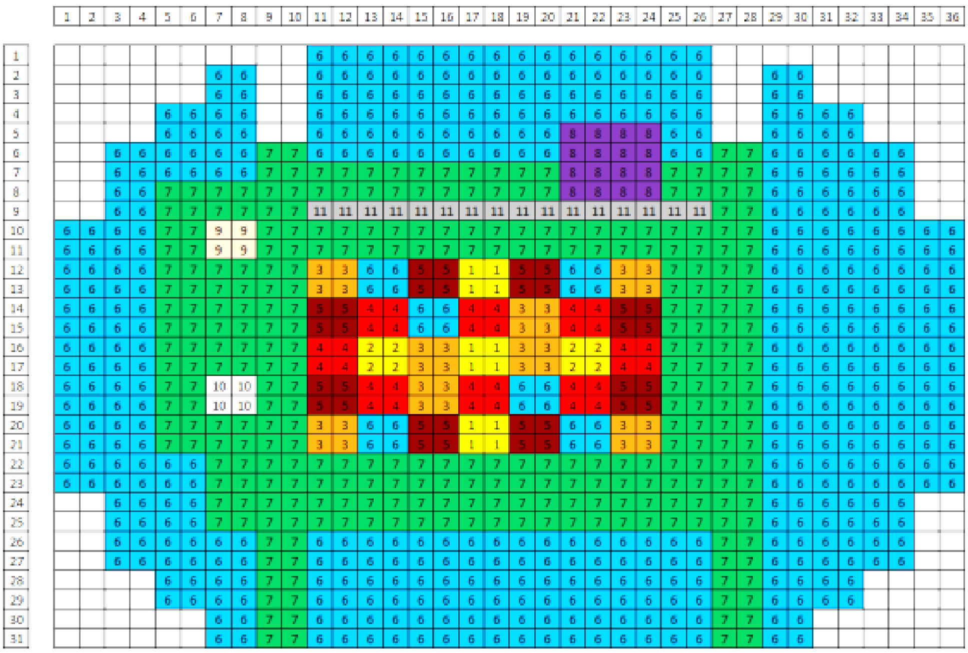


Fig.3.1 Three dimensional REMARK model of reactor core



1-2: Control rod with fuel follower
3-5: Standard fuel element
6: Aluminum reflector element
7: Beryllium reflector element
8: OWL-2 irradiation facility
9: Hydraulic rabbit irradiation facility
10: Shroud irradiation facility
11: Gamma ray shield plate

Fig.3.2 Radial nodalization of REMARK model of reactor core[10]

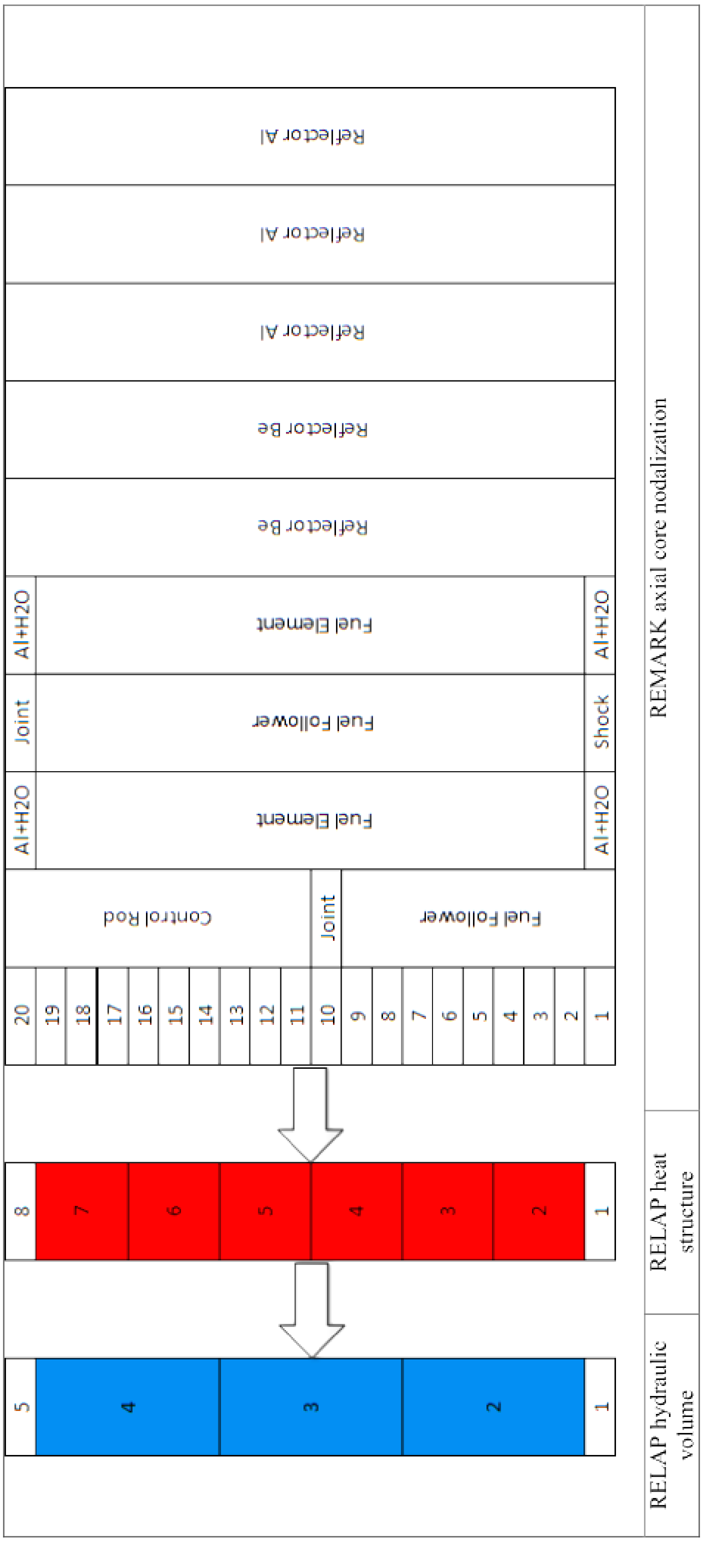


Fig.3.3 Axial nodalization of REMARK model and RELAP5-HD model of reactor core[10]

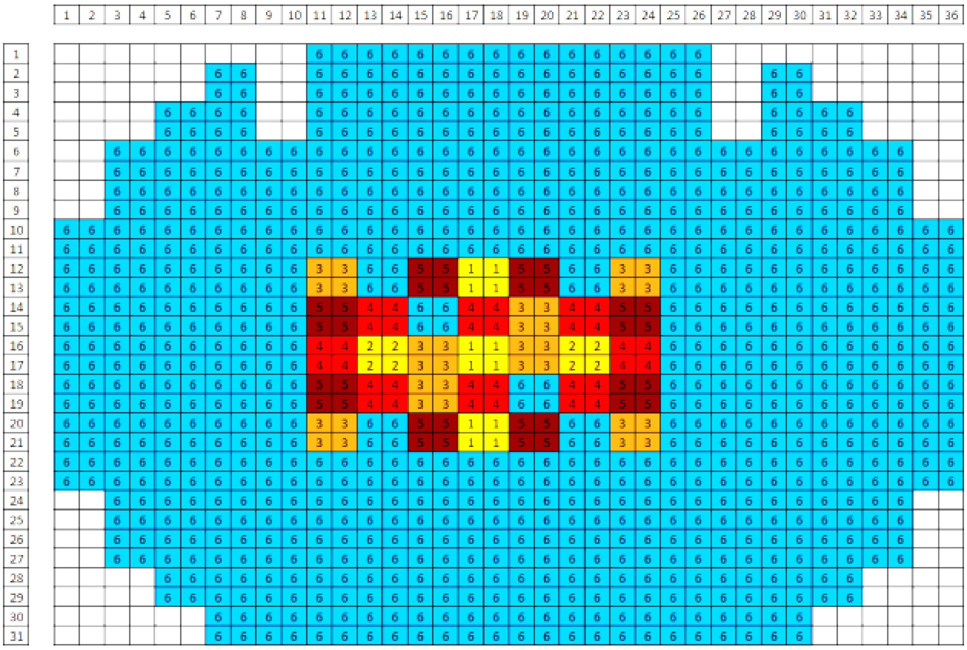
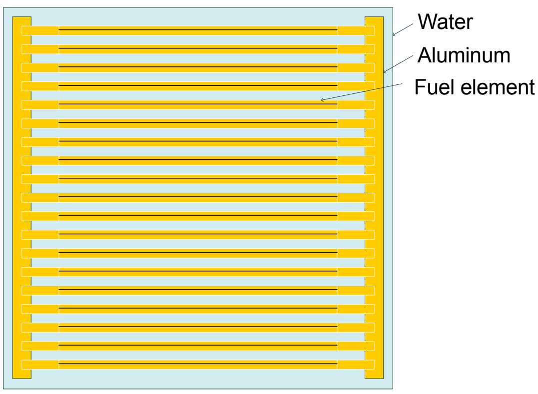
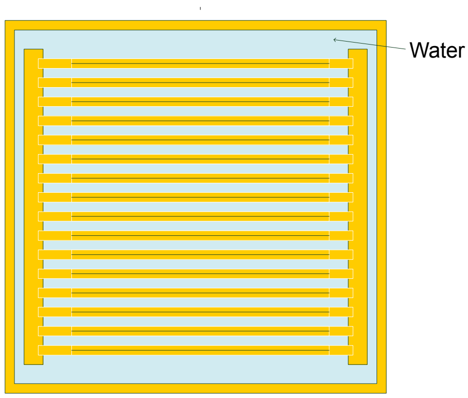


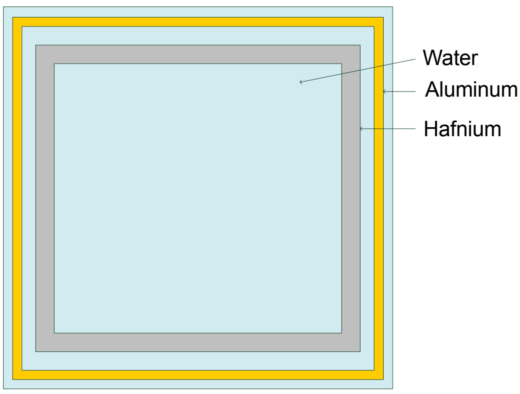
Fig.3.4 Radial Mapping of RELAP5-HD



(1) Standard fuel element



(2) Fuel follower



(3) Control rod

Fig.3.5 Radial model of fuel element and control rod

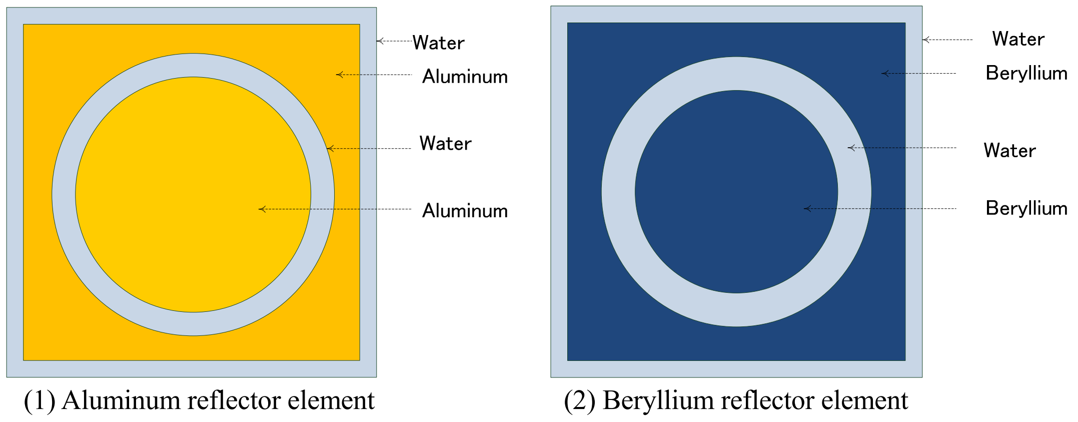
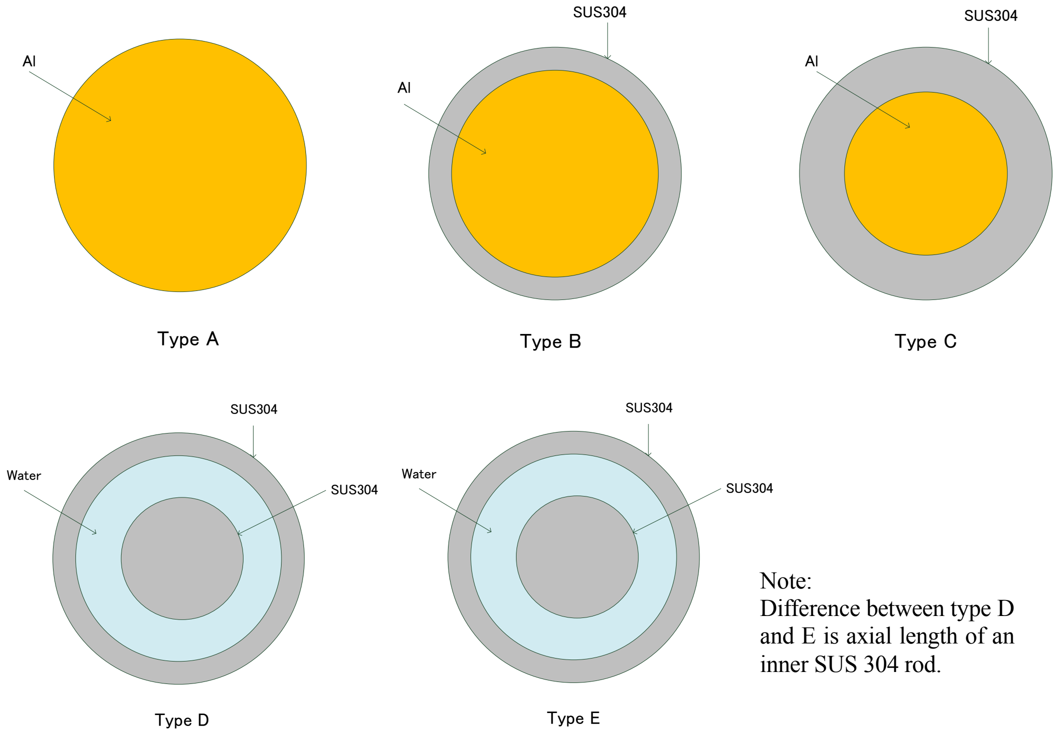


Fig.3.6 Radial model of reflector



Note:
Difference between type D and E is axial length of an inner SUS 304 rod.

Fig.3.7 Radial model of reactivity adjustment rod (type A to E)

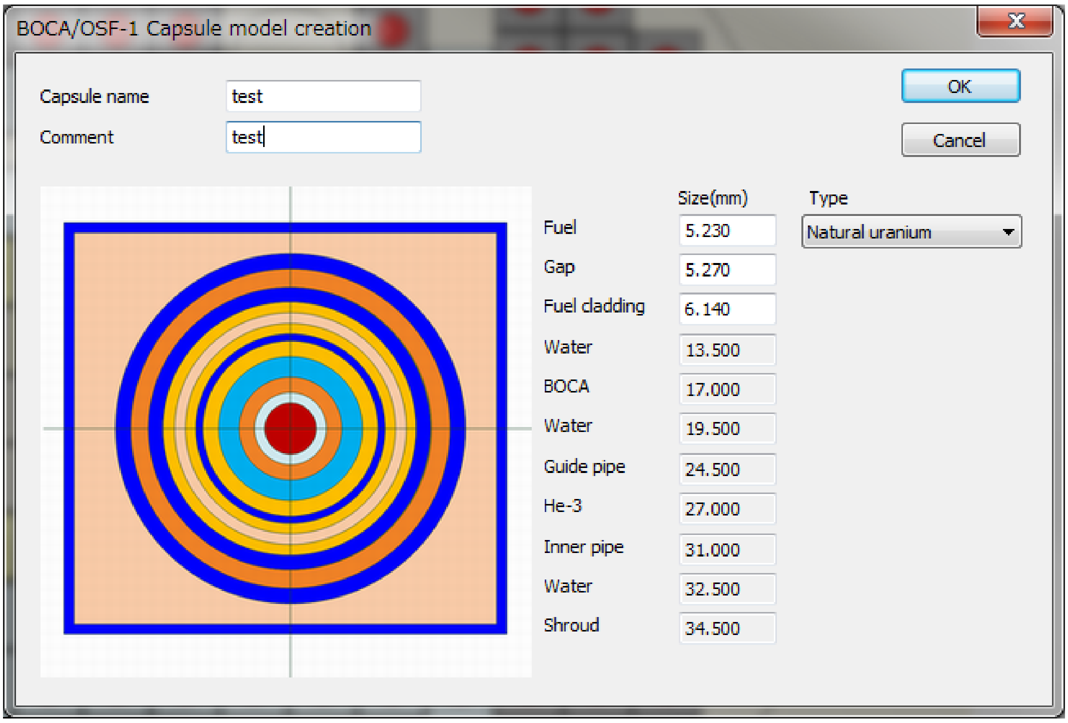


Fig.3.8 GUI of Irradiation Facility Design Support system

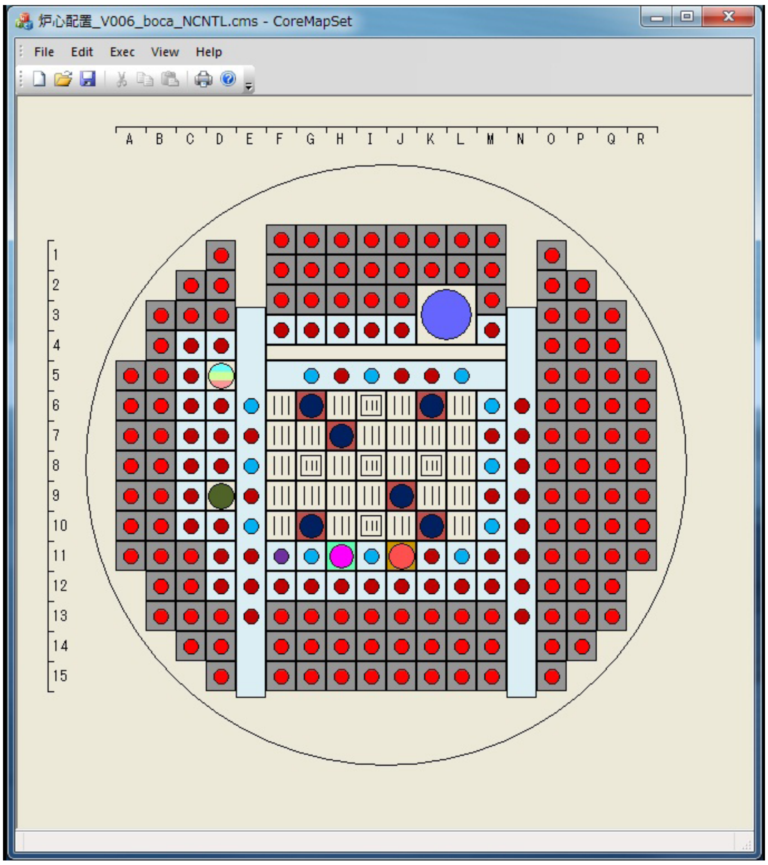


Fig.3.9 Core arrangement in Cell Distribution Support system

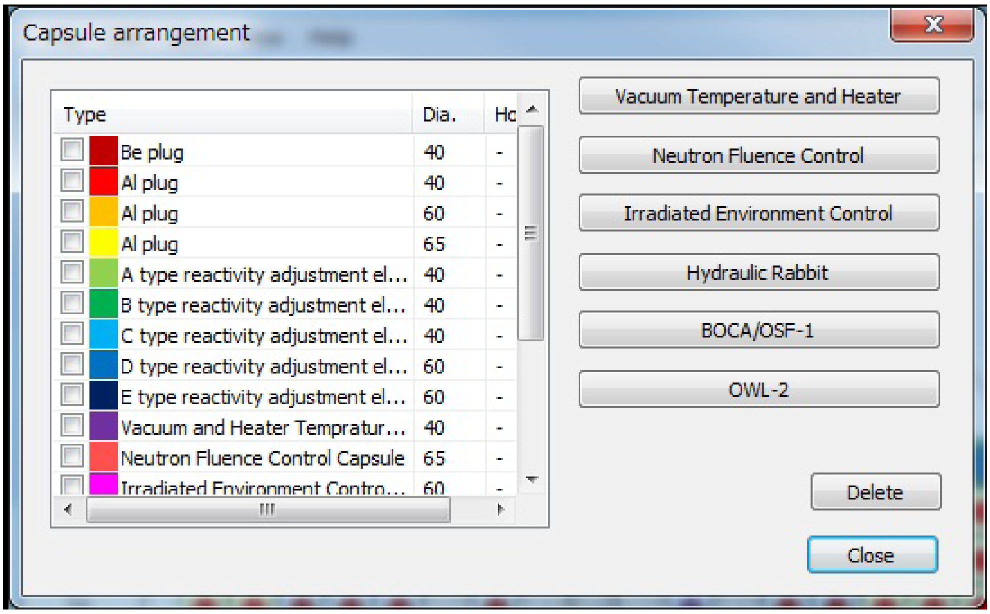


Fig.3.10 Core element selection in Cell Distribution Support system

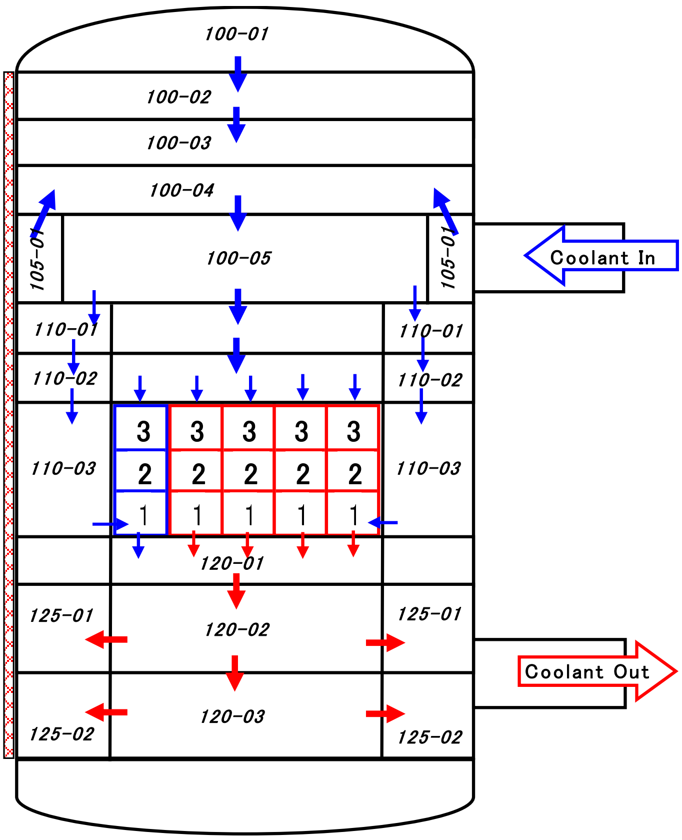


Fig.3.11 Nodalization of reactor pressure vessel overlaid on a diagram[8]

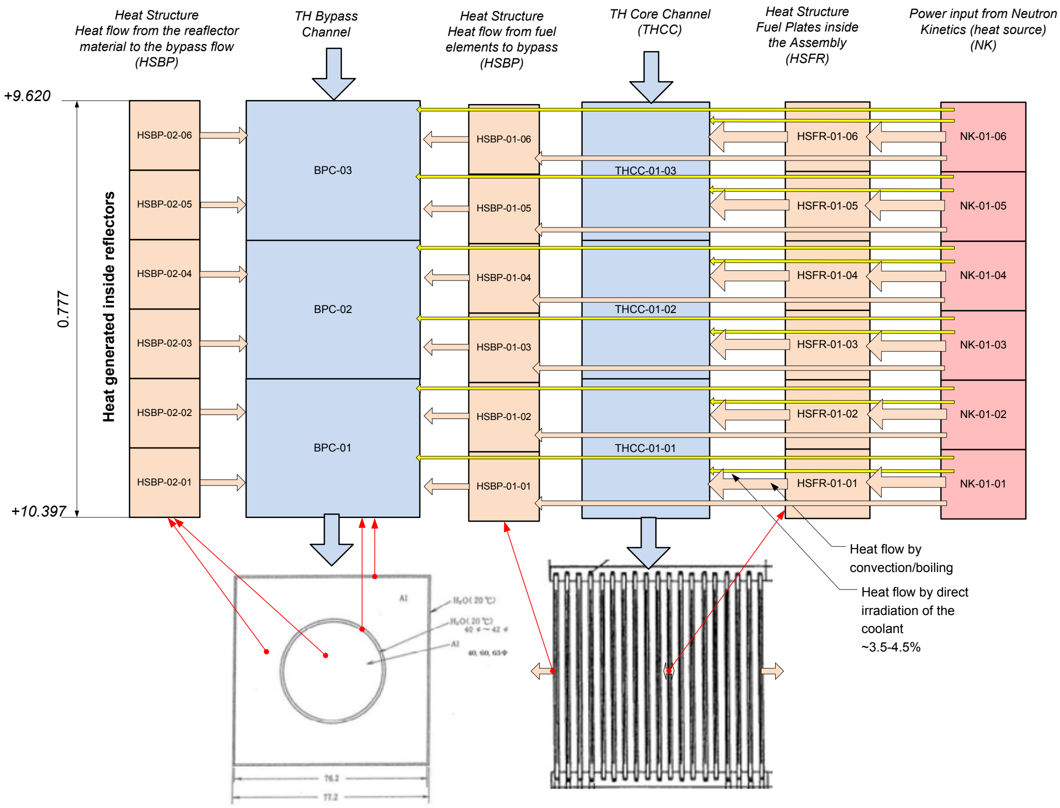


Fig.3.12 Nodalization of hydraulic channels and heat structure models of reactor core[10]

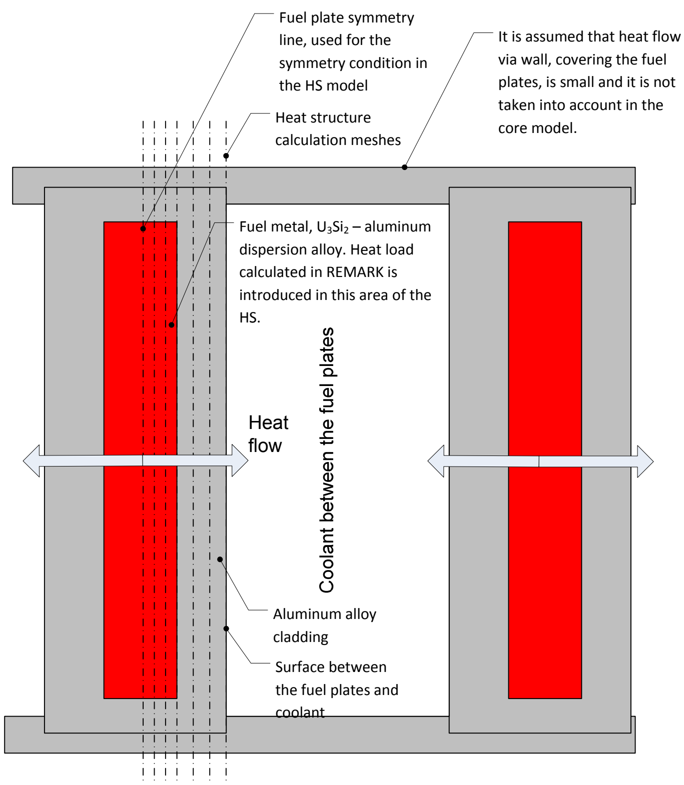


Fig.3.13 Heat structure model of fuel plate[8]

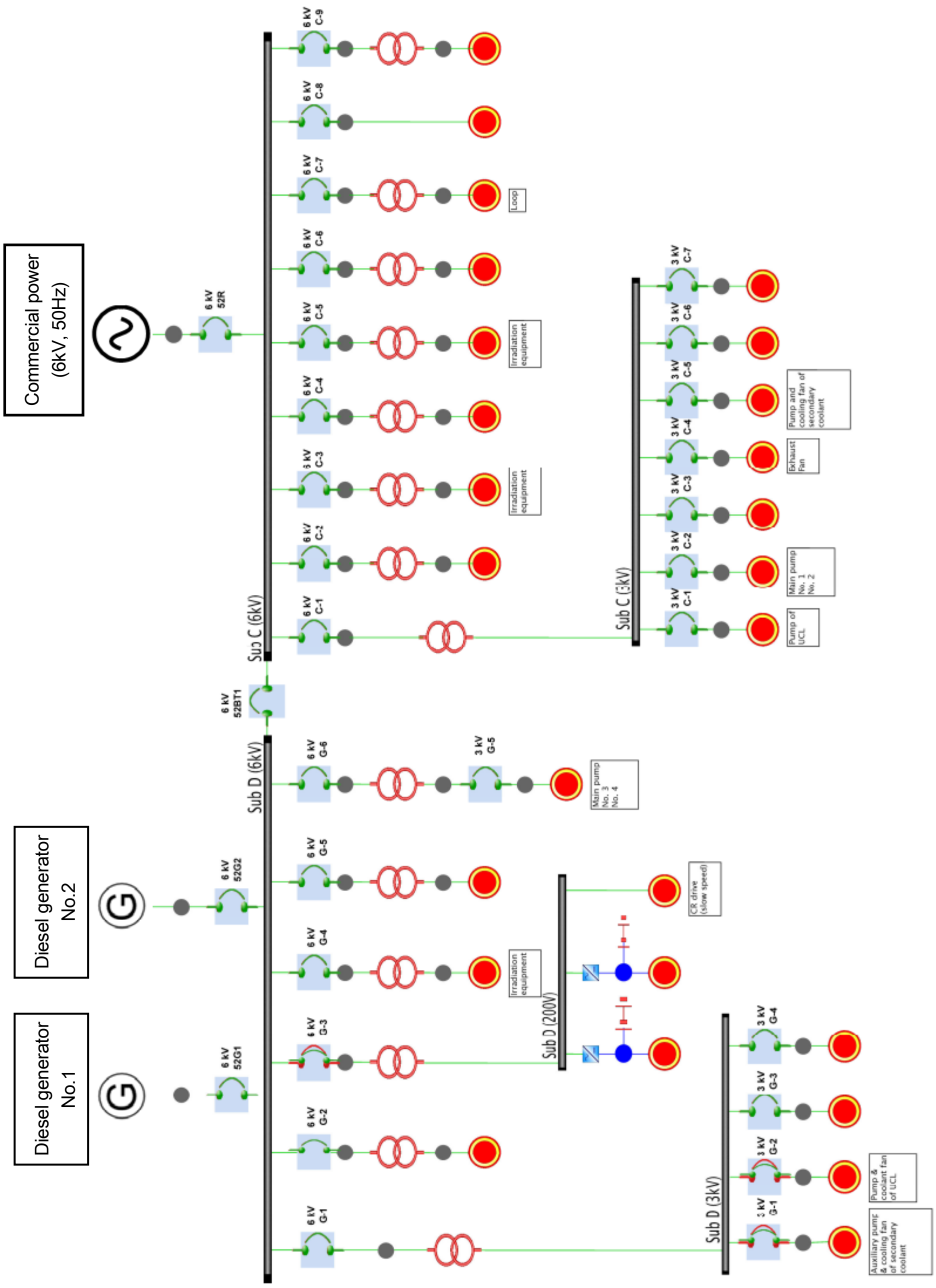


Fig.3.14 Electric system model

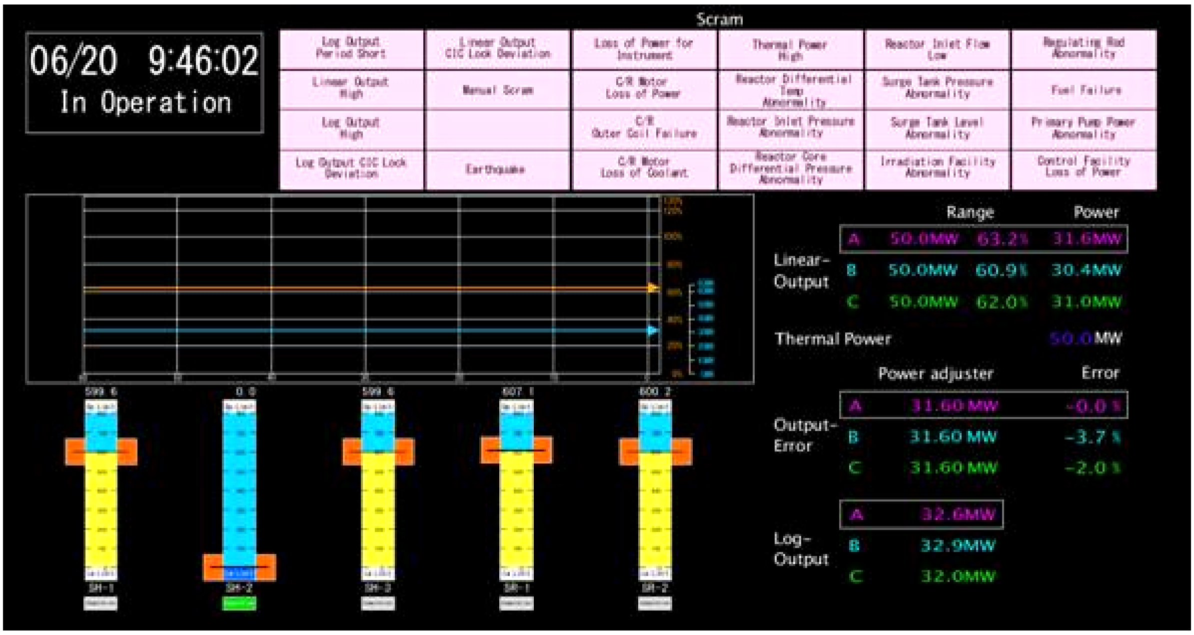


Fig.3.15 Operation screen of reactor control system

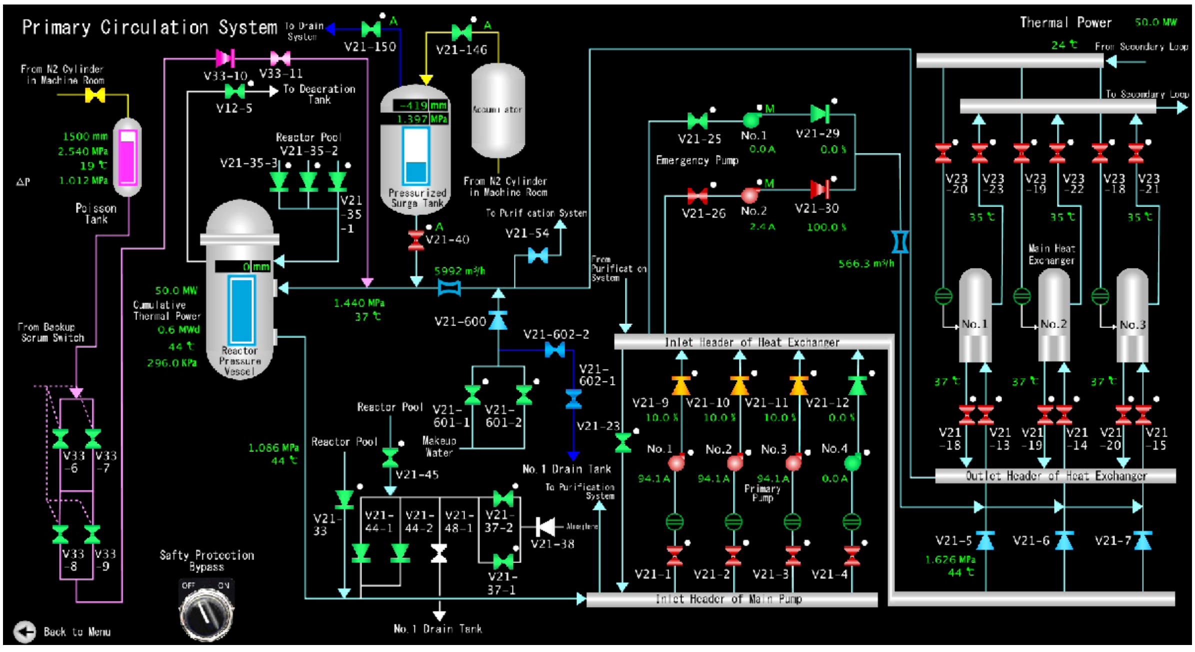


Fig.3.16 Operation screen of primary cooling system

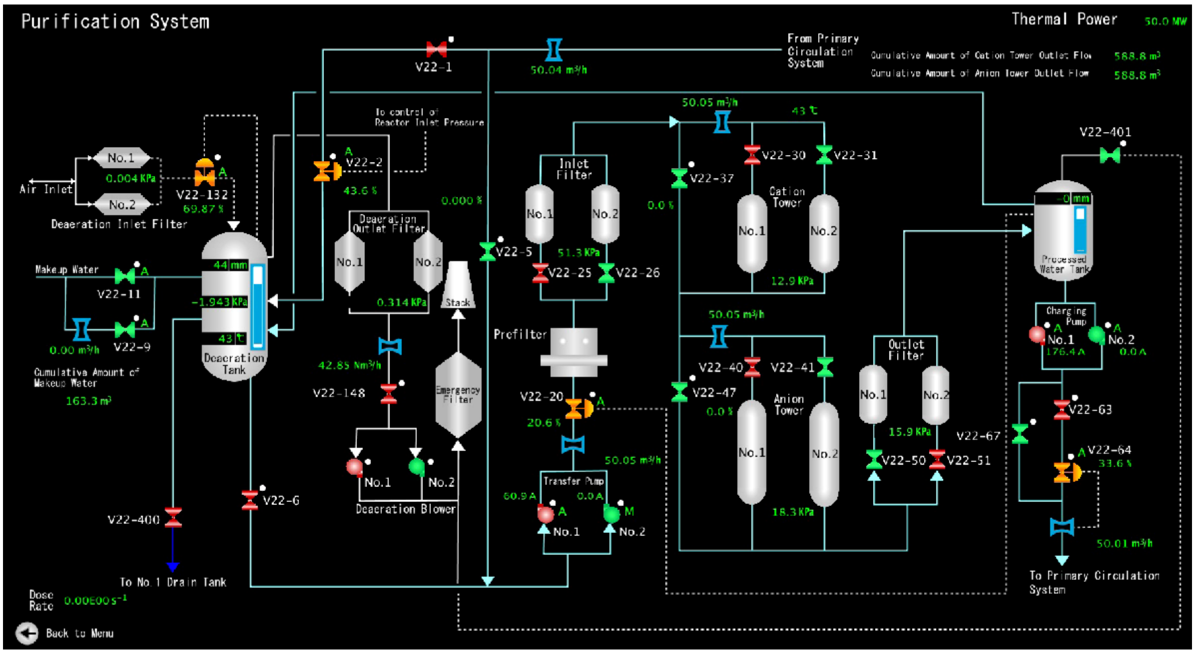


Fig.3.17 Operation screen of purification system

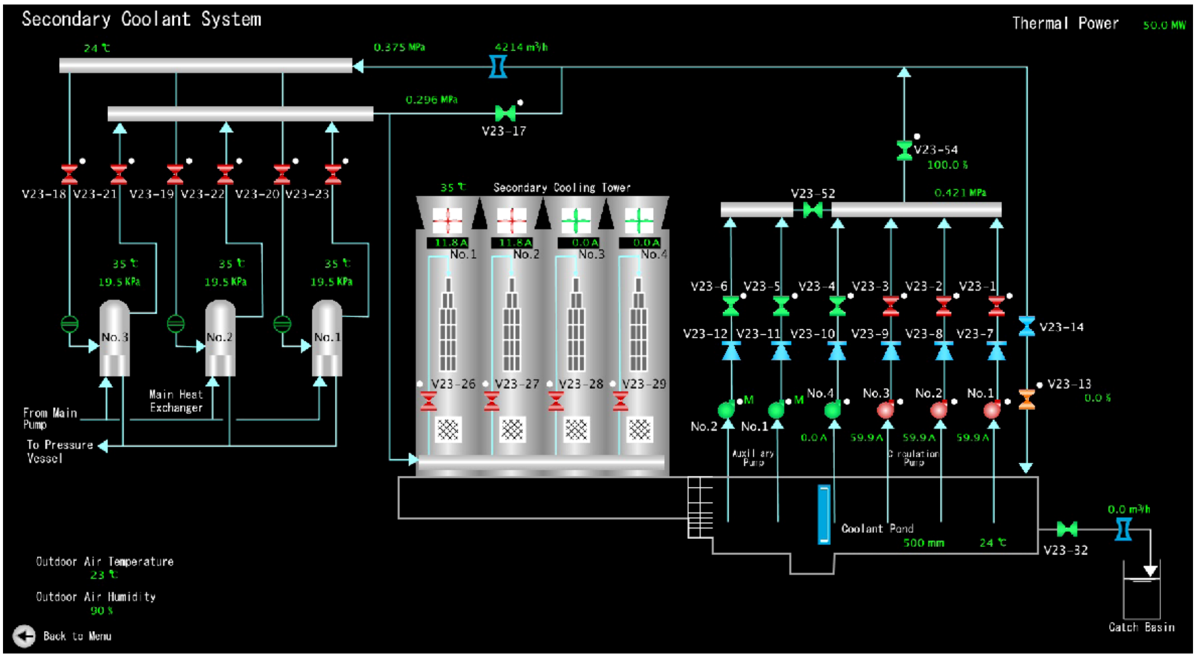


Fig.3.18 Operation screen of secondary cooling system

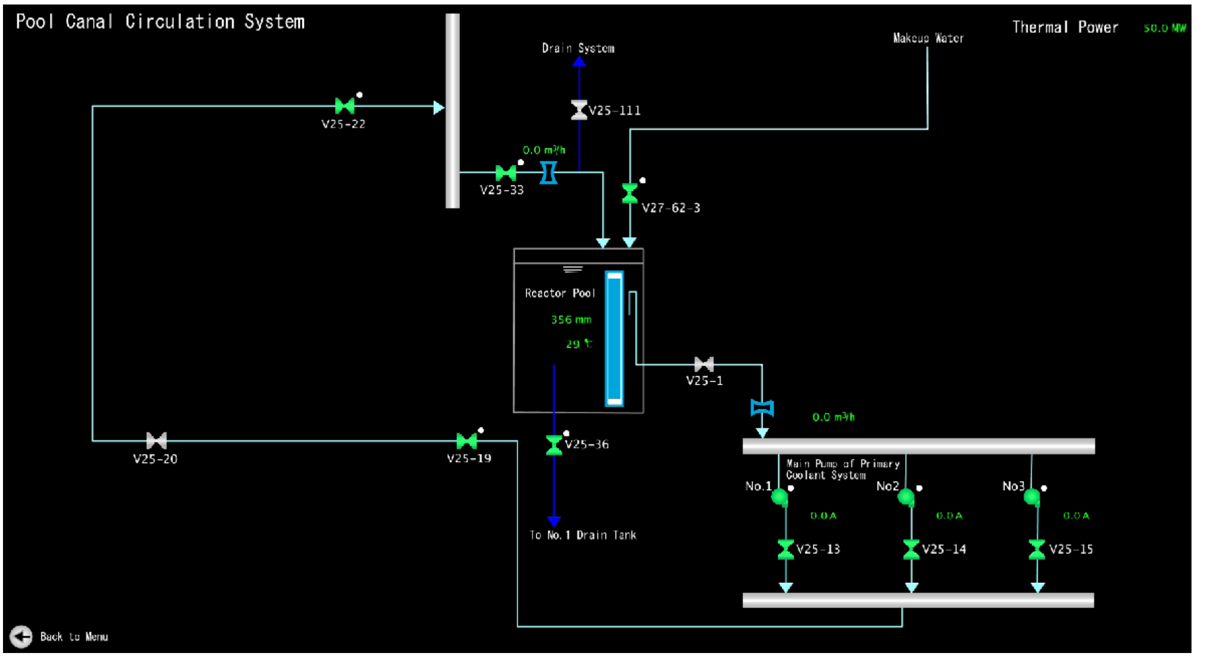


Fig.3.19 Operation screen of pool canal cooling system

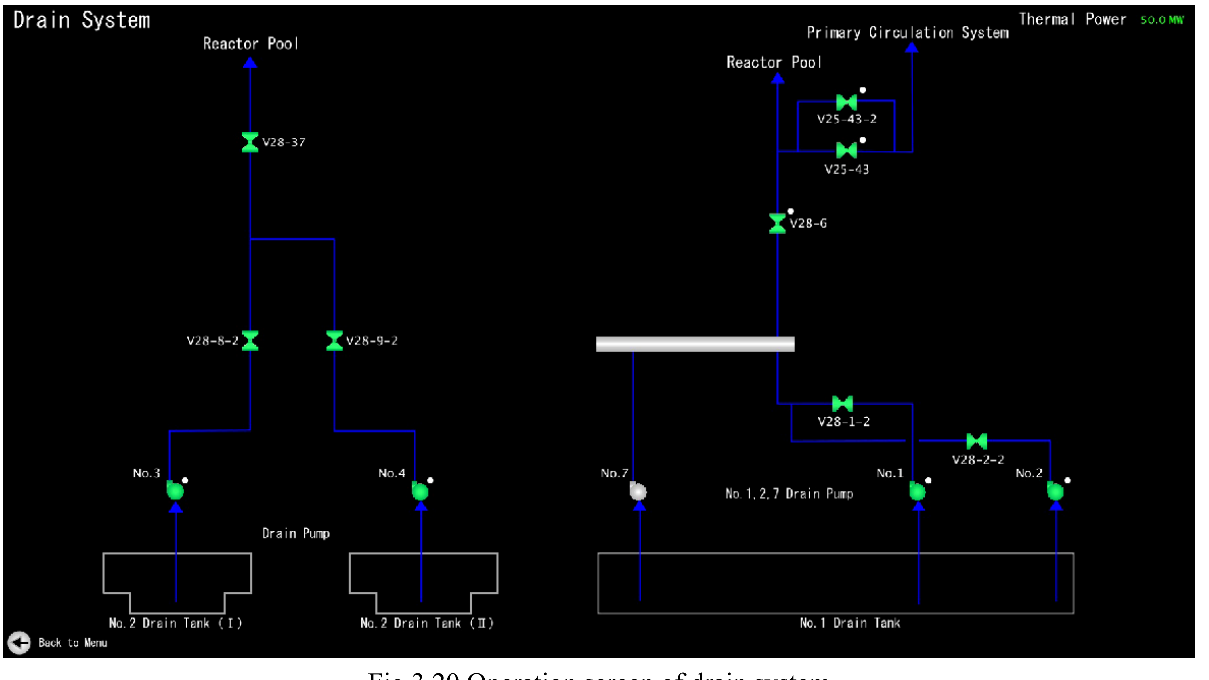


Fig.3.20 Operation screen of drain system

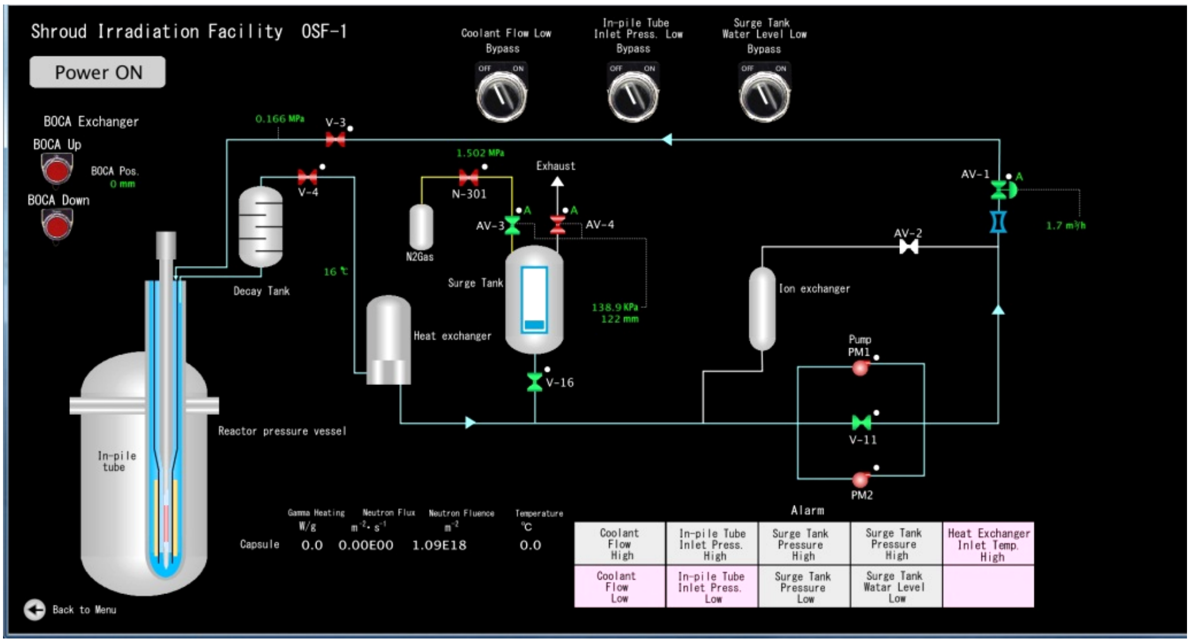


Fig.3.21 Operation screen of shroud irradiation facility

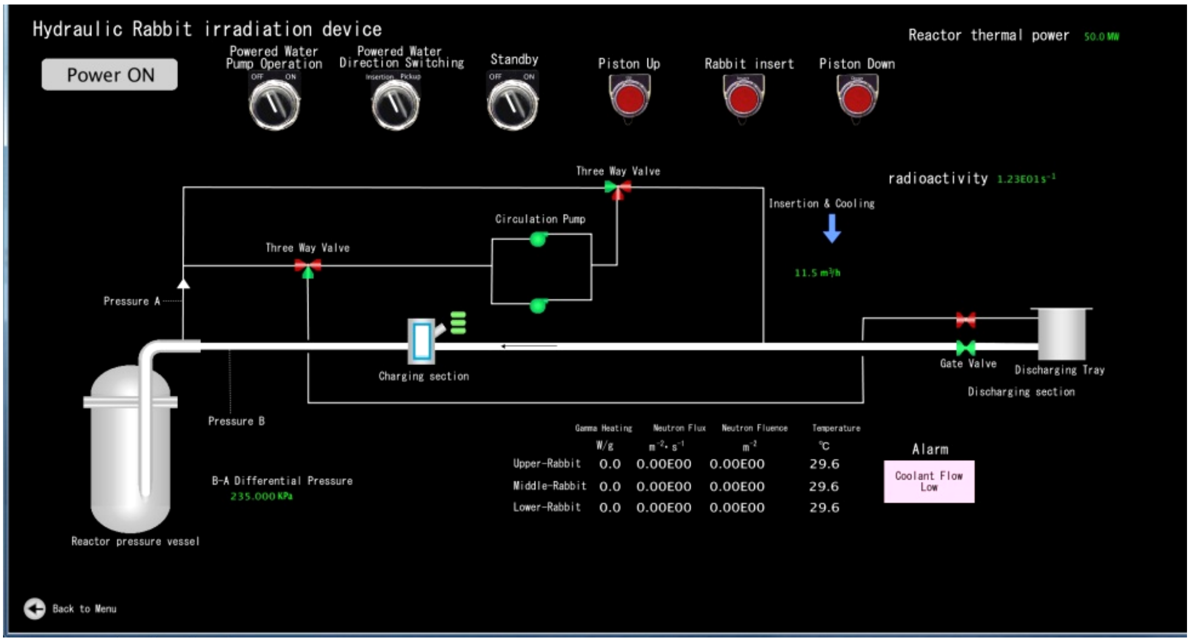


Fig.3.22 Operation screen of hydraulic rabbit irradiation facility

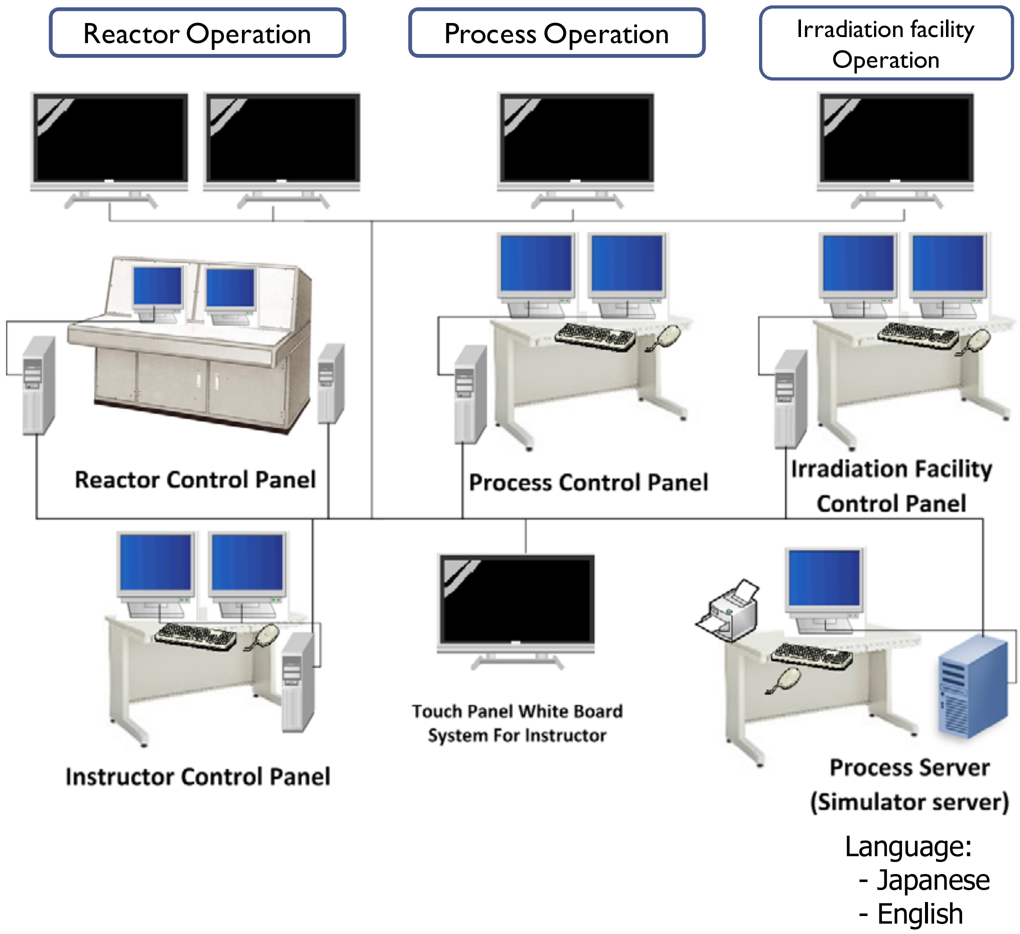


Fig.4.1 Schematic drawing of hardware configuration

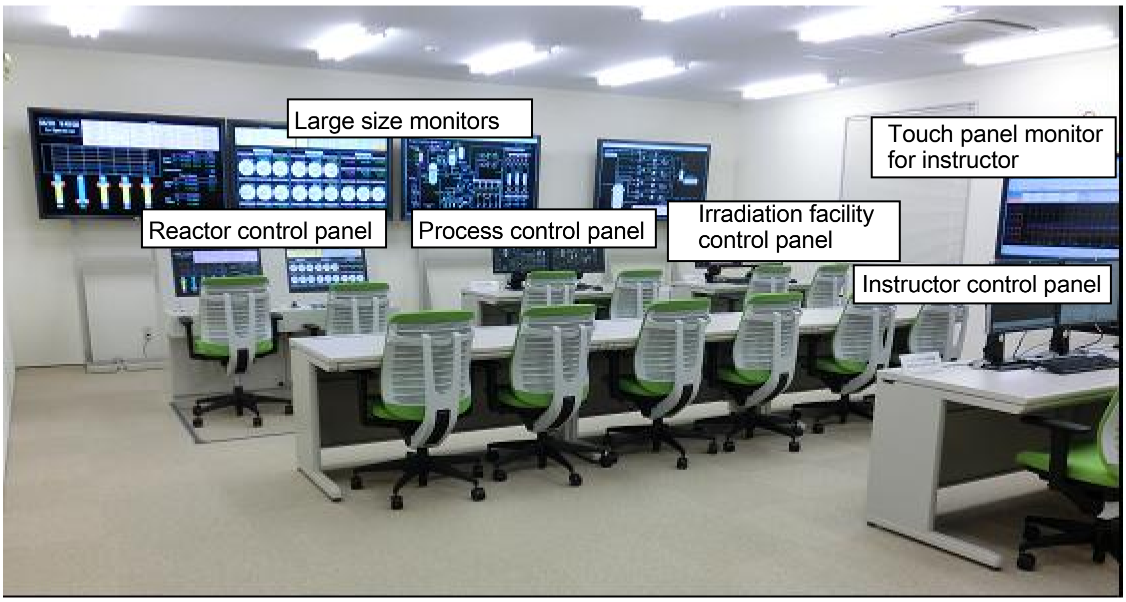
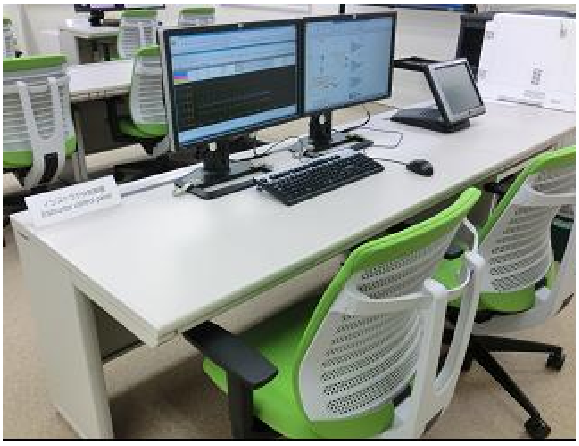


Fig.4.2 Simulator room

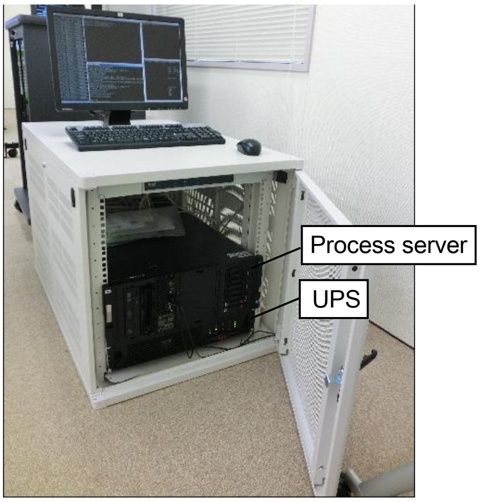
(a) Reactor control panel

(b) Process control panel

(c) Irradiation facility control panel



(d) Instructor control panel



(e) Process server with UPS

Fig.4.3 Control panels and process server

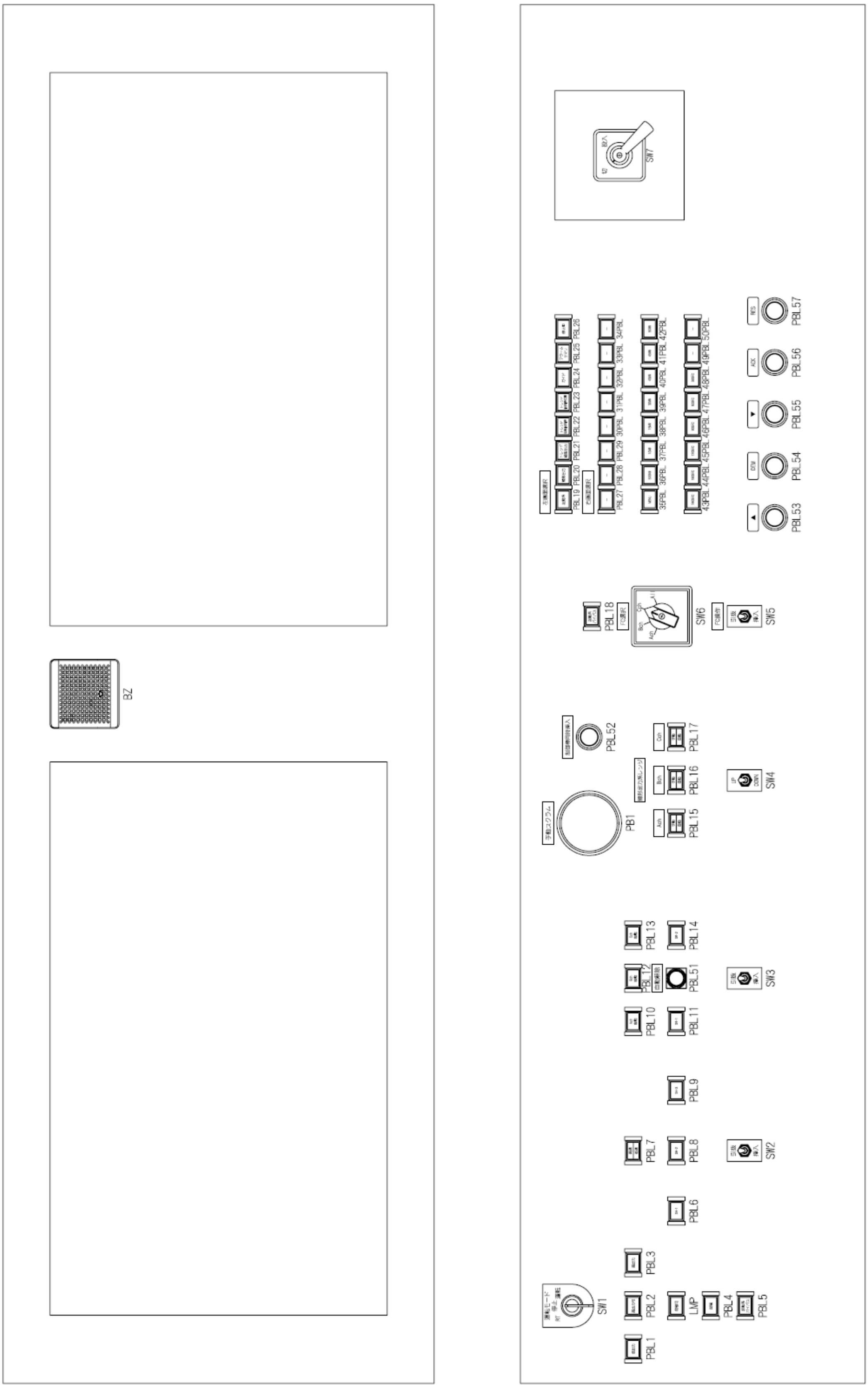


Fig.4.4 Outer shape of reactor control panel

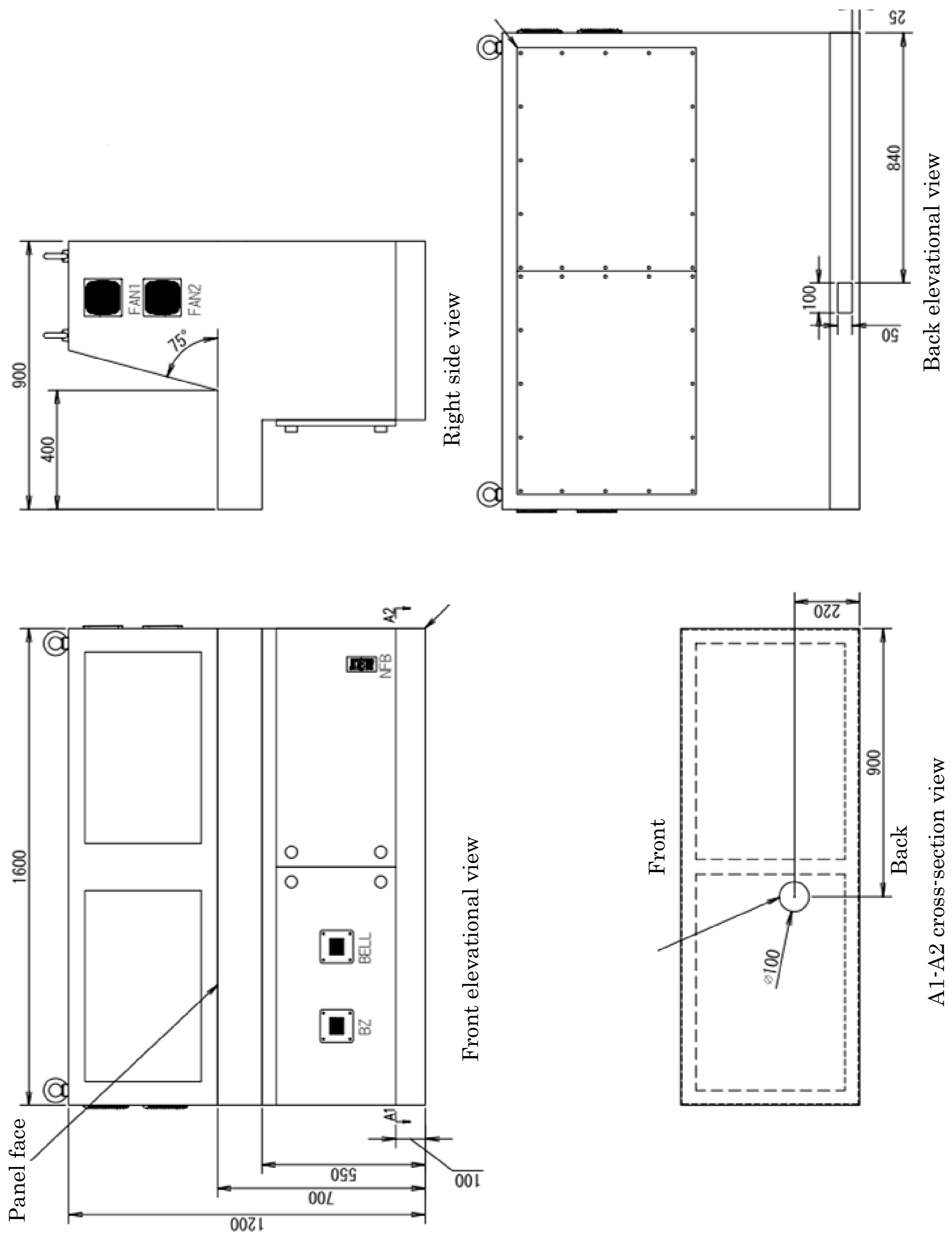


Fig.4.5 Outer shape of reactor control panel

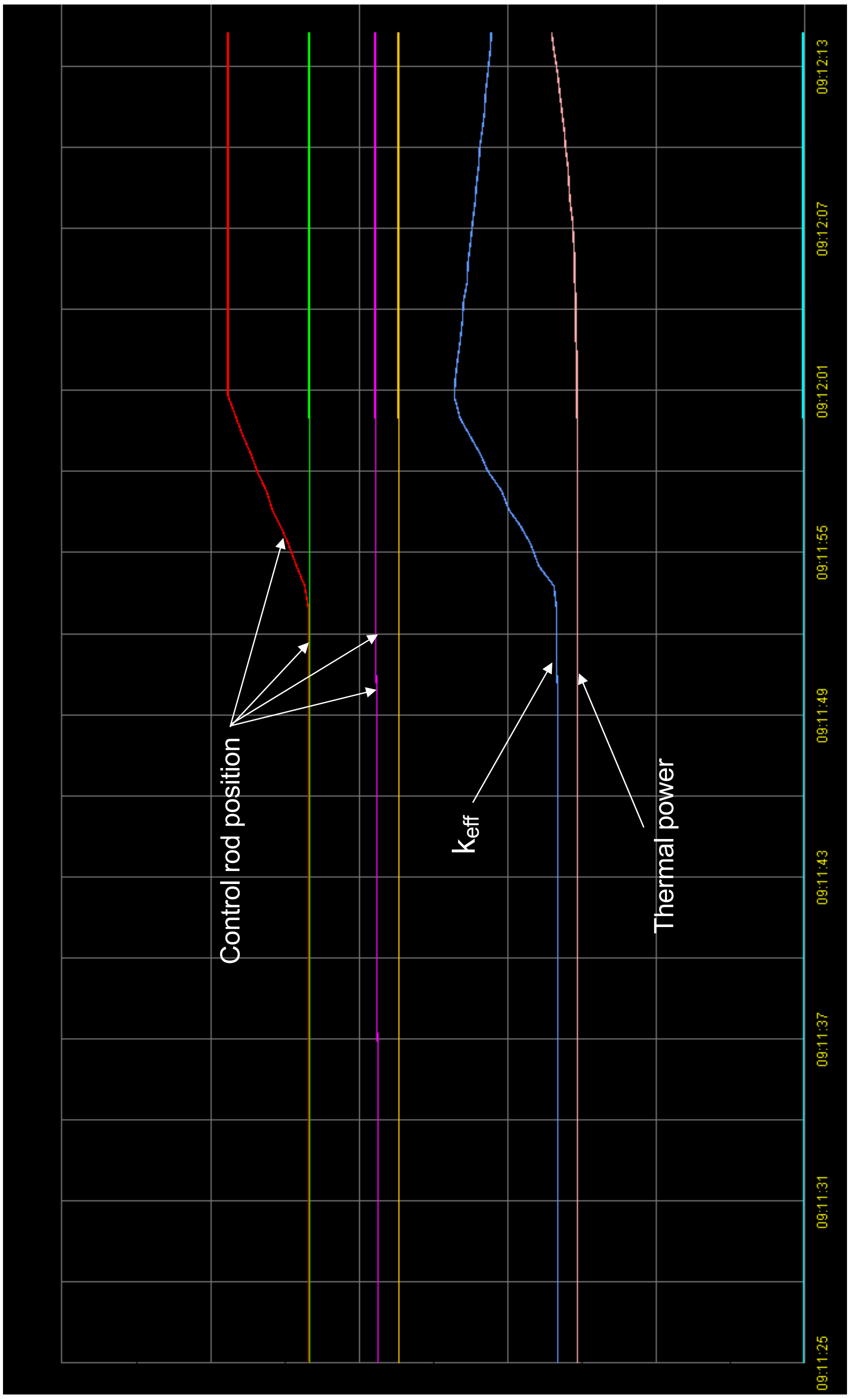


Fig.5.1 Trend graph of typical reactor parameters

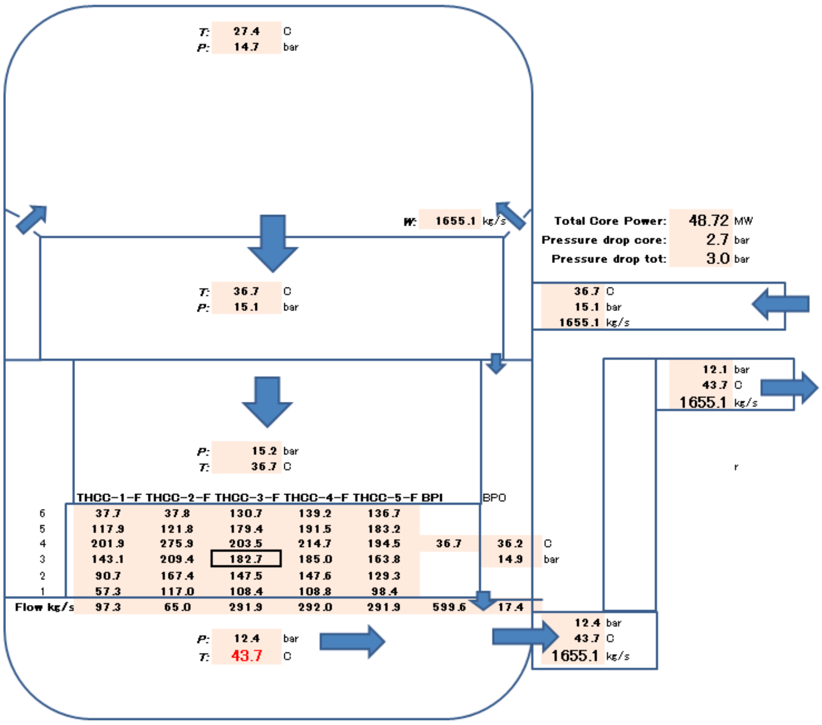


Fig.5.2 Output of coolant and fuel temperature in the reactor pressure vessel

[Unit : n/cm^2·s]

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
1				8.85E+12	1.18E+13	9.06E+12	1.07E+13	1.18E+13	1.25E+13	1.22E+13	1.11E+13	9.46E+12	7.52E+12	8.94E+12	6.34E+12			
2			1.13E+13	1.69E+13	2.27E+13	2.07E+13	2.46E+13	2.78E+13	2.96E+13	2.89E+13	2.59E+13	2.19E+13	1.68E+13	1.59E+13	1.08E+13	6.87E+12		
3		1.06E+13	1.92E+13	3.12E+13	5.02E+13	3.86E+13	4.59E+13	5.35E+13	5.81E+13	5.69E+13	4.95E+13	4.19E+13	3.00E+13	2.93E+13	1.70E+13	1.11E+13	6.55E+12	
4		1.63E+13	4.64E+13	9.26E+13	1.42E+14	1.14E+14	1.28E+14	1.61E+14	1.84E+14	1.78E+14	1.51E+14	1.24E+14	8.29E+13	6.69E+13	2.68E+13	1.64E+13	9.20E+12	
5	9.44E+12	2.40E+13	8.28E+13	1.49E+14	2.27E+14	2.16E+14	1.45E+14	3.06E+14	3.85E+14	3.72E+14	2.76E+14	1.17E+14	1.40E+14	1.01E+14	3.87E+13	2.28E+13	1.21E+13	5.40E+12
6	1.17E+13	3.08E+13	1.10E+14	2.25E+14	3.00E+14	1.52E+14	1.62E+14	2.08E+14	2.45E+14	2.36E+14	1.94E+14	1.29E+14	1.30E+14	1.35E+14	5.23E+13	2.97E+13	1.51E+13	6.47E+12
7	1.32E+13	3.50E+13	1.28E+14	2.69E+14	3.22E+14	2.09E+14	1.97E+14	1.99E+14	1.94E+14	1.94E+14	2.12E+14	2.20E+14	3.27E+14	2.11E+14	6.72E+13	3.57E+13	1.75E+13	7.34E+12
8	1.35E+13	3.57E+13	1.27E+14	2.24E+14	1.84E+14	2.00E+14	2.13E+14	1.79E+14	9.03E+13	1.80E+14	2.17E+14	2.29E+14	3.97E+14	2.46E+14	7.36E+13	3.80E+13	1.84E+13	7.65E+12
9	1.28E+13	3.37E+13	1.24E+14	2.22E+14	2.87E+14	2.15E+14	2.11E+14	1.83E+14	1.94E+14	2.01E+14	1.98E+14	2.08E+14	3.18E+14	2.07E+14	6.62E+13	3.52E+13	1.73E+13	7.27E+12
10	1.13E+13	2.87E+13	9.25E+13	2.15E+14	3.00E+14	1.62E+14	1.80E+14	2.31E+14	2.51E+14	2.21E+14	1.79E+14	1.21E+14	1.24E+14	1.30E+14	5.09E+13	2.90E+13	1.48E+13	6.35E+12
11	9.58E+12	2.42E+13	5.07E+13	1.53E+14	2.60E+14	2.48E+14	1.66E+14	3.50E+14	4.22E+14	3.85E+14	2.75E+14	1.11E+14	1.36E+14	9.62E+13	3.72E+13	2.21E+13	1.18E+13	5.28E+12
12		1.77E+13	3.23E+13	8.24E+13	1.57E+14	1.71E+14	1.70E+14	2.31E+14	2.64E+14	2.44E+14	1.86E+14	1.18E+14	9.56E+13	6.27E+13	2.57E+13	1.58E+13	8.80E+12	
13		1.17E+13	2.00E+13	3.22E+13	6.58E+13	6.73E+13	6.98E+13	7.85E+13	8.36E+13	7.85E+13	6.52E+13	5.06E+13	4.22E+13	3.46E+13	1.65E+13	1.07E+13	6.33E+12	
14			1.20E+13	1.79E+13	3.29E+13	3.80E+13	3.97E+13	4.24E+13	4.36E+13	4.12E+13	3.59E+13	3.00E+13	2.59E+13	2.05E+13	1.02E+13	6.94E+12		
15				9.29E+12	1.56E+13	1.98E+13	2.10E+13	2.19E+13	2.21E+13	2.11E+13	1.90E+13	1.65E+13	1.44E+13	1.06E+13	5.81E+12			

Fig.5.3 Output of neutron flux distribution at the core

国際単位系（SI）

表１．SI 基本単位

基本量	SI 基本単位 名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd

表２．基本単位を用いて表されるSI組立単位の例

組立量	SI 基本単位 名称	記号
面積	平方メートル	m^{2}
体積	立法メートル	m^{3}
速さ，速度	メートル毎秒	m/s
加速度	メートル毎秒毎秒	m/s^{2}
波数	毎メートル	m^{-1}
密度，質量密度	キログラム毎立方メートル	kg/m^{3}
面積密度	キログラム毎平方メートル	kg/m^{2}
比体積	立方メートル毎キログラム	m^{3}/kg
電流密度	アンペア毎平方メートル	A/m^{2}
磁界の強さ	アンペア毎メートル	A/m
量濃度(a)，濃度	モル毎立方メートル	mol/m^{3}
質量濃度	キログラム毎立法メートル	kg/m^{3}
輝度	カンデラ毎平方メートル	cd/m^{2}
屈折率(b)	（数字の） 1	1
比透磁率(b)	（数字の） 1	1

(a) 量濃度（amount concentration）は臨床化学の分野では物質濃度（substance concentration）ともよばれる。
(b) これらは無次元量あるいは次元１をもつ量であるが、そのことを表す単位記号である数字の１は通常は表記しない。

表３．固有の名称と記号で表されるSI組立単位

組立量	SI 組立単位 名称	記号	他のSI単位による表し方	SI基本単位による表し方
平面角	ラジアン(b)	rad	1(b)	m/m
立体角	ステラジアン(b)	sr(c)	1(b)	m^{2}/m^{2}
周波数	ヘルツ(d)	Hz		s^{-1}
力	ニュートン	N		m kg s^{-2}
圧力，応力	パスカル	Pa	N/m^{2}	m^{-1} kg s^{-2}
エネルギー，仕事，熱量	ジュール	J	N m	m^{2} kg s^{-2}
仕事率，工率，放射束	ワット	W	J/s	m^{2} kg s^{-3}
電荷，電気量	クーロン	C		s A
電位差（電圧），起電力	ボルト	V	W/A	m^{2} kg s^{-3} A^{-1}
静電容量	ファラド	F	C/V	m^{-2} kg^{-1} s^{4} A^{2}
電気抵抗	オーム	Ω	V/A	m^{2} kg s^{-3} A^{-2}
コンダクタンス	ジーメンス	S	A/V	m^{-2} kg^{-1} s^{3} A^{2}
磁束	ウエーバ	Wb	Vs	m^{2} kg s^{-2} A^{-1}
磁束密度	テスラ	T	Wb/m^{2}	kg s^{-2} A^{-1}
インダクタンス	ヘンリー	H	Wb/A	m^{2} kg s^{-2} A^{-2}
セルシウス温度	セルシウス度(e)	℃		K
光束	ルーメン	lm	cd sr(c)	cd
照度	ルクス	lx	lm/m^{2}	m^{-2} cd
放射性核種の放射能(f)	ベクレル(d)	Bq		s^{-1}
吸収線量, 比エネルギー分与, カーマ	グレイ	Gy	J/kg	m^{2} s^{-2}
線量当量, 周辺線量当量, 方向性線量当量, 個人線量当量	シーベルト(g)	Sv	J/kg	m^{2} s^{-2}
酸素活性	カタール	kat		s^{-1} mol

(a)SI接頭語は固有の名称と記号を持つ組立単位と組み合わせても使用できる。しかし接頭語を付した単位はもはやコヒーレントではない。
(b)ラジアンとステラジアンは数字の１に対する単位の特別な名称で、量についての情報をつたえるために使われる。実際には、使用する時には記号rad及びsrが用いられるが、習慣として組立単位としての記号である数字の１は明示されない。
(c)測光学ではステラジアンという名称と記号srを単位の表し方の中に、そのまま維持している。
(d)ヘルツは周期現象についてのみ、ベクレルは放射性核種の統計的過程についてのみ使用される。
(e)セルシウス度はケルビンの特別な名称で、セルシウス温度を表すために使用される。セルシウス度とケルビンの単位の大きさは同一である。したがって、温度差や温度間隔を表す数値はどちらの単位で表しても同じである。
(f)放射性核種の放射能（activity referred to a radionuclide）は、しばしば誤った用語で"radioactivity"と記される。
(g)単位シーベルト（PV,2002,70,205）についてはCIPM勧告2（CI-2002）を参照。

表４．単位の中に固有の名称と記号を含むSI組立単位の例

組立量	SI 組立単位 名称	記号	SI 基本単位による表し方
粘度	パスカル秒	Pa s	m^{-1} kg s^{-1}
力のモーメント	ニュートンメートル	N m	m^{2} kg s^{-2}
表面張力	ニュートン毎メートル	N/m	kg s^{-2}
角速度	ラジアン毎秒	rad/s	m m^{-1} s^{-1}=s^{-1}
角加速度	ラジアン毎秒毎秒	rad/s^{2}	m m^{-1} s^{-2}=s^{-2}
熱流密度，放射照度	ワット毎平方メートル	W/m^{2}	kg s^{-3}
熱容量，エントロピー	ジュール毎ケルビン	J/K	m^{2} kg s^{-2} K^{-1}
比熱容量，比エントロピー	ジュール毎キログラム毎ケルビン	J/(kg K)	m^{2} s^{-2} K^{-1}
比エネルギー	ジュール毎キログラム	J/kg	m^{2} s^{-2}
熱伝導率	ワット毎メートル毎ケルビン	W/(m K)	m kg s^{-3} K^{-1}
体積エネルギー	ジュール毎立方メートル	J/m^{3}	m^{-1} kg s^{-2}
電界の強さ	ボルト毎メートル	V/m	m kg s^{-3} A^{-1}
電荷密度	クーロン毎立方メートル	C/m^{3}	m^{-3} sA
表面電荷	クーロン毎平方メートル	C/m^{2}	m^{-2} sA
電束密度，電気変位	クーロン毎平方メートル	C/m^{2}	m^{-2} sA
誘電率	ファラド毎メートル	F/m	m^{-3} kg^{-1} s^{4} A^{2}
透磁率	ヘンリー毎メートル	H/m	m kg s^{-2} A^{-2}
モルエネルギー	ジュール毎モル	J/mol	m^{2} kg s^{-2} mol^{-1}
モルエントロピー, モル熱容量	ジュール毎モル毎ケルビン	J/(mol K)	m^{2} kg s^{-2} K^{-1} mol^{-1}
照射線量（Ｘ線及びγ線）	クーロン毎キログラム	C/kg	kg^{-1} sA
吸収線量率	グレイ毎秒	Gy/s	m^{2} s^{-3}
放射強度	ワット毎ステラジアン	W/sr	m^{4} m^{-2} kg s^{-3}=m^{2} kg s^{-3}
放射輝度	ワット毎平方メートル毎ステラジアン	W/(m^{2} sr)	m^{2} m^{-2} kg s^{-3}=kg s^{-3}
酵素活性濃度	カタール毎立方メートル	kat/m^{3}	m^{-3} s^{-1} mol

表５．SI 接頭語

乗数	接頭語	記号	乗数	接頭語	記号
10^{24}	ヨタ	Y	10^{-1}	デシ	d
10^{21}	ゼタ	Z	10^{-2}	センチ	c
10^{18}	エクサ	E	10^{-3}	ミリ	m
10^{15}	ペタ	P	10^{-6}	マイクロ	µ
10^{12}	テラ	T	10^{-9}	ナノ	n
10^{9}	ギガ	G	10^{-12}	ピコ	p
10^{6}	メガ	M	10^{-15}	フェムト	f
10^{3}	キロ	k	10^{-18}	アト	a
10^{2}	ヘクト	h	10^{-21}	ゼプト	z
10^{1}	デカ	da	10^{-24}	ヨクト	y

表６．SIに属さないが、SIと併用される単位

名称	記号	SI 単位による値
分	min	1 min=60s
時	h	1h =60 min=3600 s
日	d	1 d=24 h=86 400 s
度	°	1°=(π/180) rad
分	’	1’=(1/60)°=(π/10800) rad
秒	”	1”=(1/60)’=(π/648000) rad
ヘクタール	ha	1ha=1hm^{2}=10^{4}m^{2}
リットル	L，l	1L=11=1dm^{3}=10^{3}cm^{3}=10^{-3}m^{3}
トン	t	1t=10^{3} kg

表７．SIに属さないが、SIと併用される単位で、SI単位で表される数値が実験的に得られるもの

名称	記号	SI 単位で表される数値
電子ボルト	eV	1eV=1.602 176 53(14)×10^{-19}J
ダルトン	Da	1Da=1.660 538 86(28)×10^{-27}kg
統一原子質量単位	u	1u=1 Da
天文単位	ua	1ua=1.495 978 706 91(6)×10^{11}m

表８．SIに属さないが、SIと併用されるその他の単位

名称	記号	SI 単位で表される数値
バール	bar	1 bar=0.1MPa=100kPa=10^{5}Pa
水銀柱ミリメートル	mmHg	1mmHg=133.322Pa
オングストローム	Å	1 Å=0.1nm=100pm=10^{-10}m
海里	M	1 M=1852m
バーン	b	1 b=100fm^{2}=(10^{-12}cm)2=10^{-28}m^{2}
ノット	kn	1 kn=(1852/3600)m/s
ネーパ	Np	SI単位との数値的な関係は、対数量の定義に依存。
ベル	B	
デジベル	dB	

表９．固有の名称をもつCGS組立単位

名称	記号	SI 単位で表される数値
エルグ	erg	1 erg=10^{-7} J
ダイン	dyn	1 dyn=10^{-5}N
ポアズ	P	1 P=1 dyn s cm^{-2}=0.1Pa s
ストークス	St	1 St =1cm^{2} s^{-1}=10^{-4}m^{2} s^{-1}
スチルブ	sb	1 sb =1cd cm^{-2}=10^{4}cd m^{-2}
フォト	ph	1 ph=1cd sr cm^{-2} 10^{4}lx
ガル	Gal	1 Gal =1cm s^{-2}=10^{-2}ms^{-2}
マクスウェル	Mx	1 Mx = 1G cm^{2}=10^{-8}Wb
ガウス	G	1 G =1Mx cm^{-2} =10^{-4}T
エルステッド(c)	Oe	1 Oe ≙ (10^{3}/4π)A m^{-1}

(c) ３元系のCGS単位系とSIでは直接比較できないため、等号「 ≙ 」は対応関係を示すものである。

表10．SIに属さないその他の単位の例

名称	記号	SI 単位で表される数値
キュリー	Ci	1 Ci=3.7×10^{10}Bq
レントゲン	R	1 R = 2.58×10^{-4}C/kg
ラド	rad	1 rad=1cGy=10^{-2}Gy
レム	rem	1 rem=1 cSv=10^{-2}Sv
ガンマ	γ	1γ=1 nT=10-9T
フェルミ		1フェルミ=1 fm=10-15m
メートル系カラット		1メートル系カラット = 200 mg = 2×10-4kg
トル	Torr	1 Torr = (101 325/760) Pa
標準大気圧	atm	1 atm = 101 325 Pa
カロリー	cal	1cal=4.1858J（「15℃」カロリー），4.1868J（「IT」カロリー）4.184J（「熱化学」カロリー）
ミクロン	µ	1 µ =1µm=10^{-6}m

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